STUDY OF HYBRID ACTIVE POWER FILTER FOR POWER QUALITY IMPROVEMENT

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Technology

In

Power Electronics and Drives

By

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CERTIFICATE

This is to certify that the thesis entitled "**Study Of Hybrid Active Power Filter For Power Quality Improvement**", submitted by **Mr. Azmera Sandeep** in partial fulfillment of the requirements for the award of **Master of Technology in Electrical Engineering** with specialization in "**Power Electronics and Drives**" at National Institute of Technology, Rourkela. A bona fide record of research work carried out by him under my supervision and guidance. The candidate has fulfilled all the prescribed requirements. The Thesis which is based on candidates own work, has not submitted elsewhere for a degree/diploma.

In my opinion, the thesis is of standard required for the award of a master of technology Degree in Electrical Engineering.

Place: Rourkela

Date:

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Dedicated

To

My beloved Parents

CONTENTS

ABSTRACT

Now-a-days with the advancement of technology, the demand for electric power is increasing at an exponential rate. Many consumer appliances demand quality power continuously for their operation. The performance of the end user equipment is heavily dependent on the quality of power supplied to it. But the quality of power delivered to the end user is affected by various external and internal factors. They are like voltage and frequency variations, faults, outages etc.

These power quality problems reduce the life time and efficiency of the equipment. Thus, to enhance the performance of the consumer equipment and also the overall performance of the system these problems should be mitigated.

The main affect caused by these problems is the presence of harmonics. This leads to the overheating of the equipment, insulation failure and over speeding of induction motors etc. The solution to overcome these problems is to filter out these harmonics. For this purpose there are many filters topologies present in the literature.

In this project a hybrid filter which is a combination of series active filter and shunt passive filter is studied. This project presents the control strategy to control the filter in such a way that the harmonics are reduced. The proposed control strategy is simulated in MATLAB SIMULINK and the results are presented.

LIST OF FIGURES

LIST OF TABLES

Chapter1

INTRODUCTION

Literature review

Research motivation

Thesis objectives

Organization of thesis

1.1 INTRODUCTION

Electrical energy is the most efficient and popular form of energy and the modern society is heavily dependent on the electric supply. The life cannot be imagined without the supply of electricity. At the same time the quality of the electric power supplied is also very important for the efficient functioning of the end user equipment.

The term power quality became most prominent in the power sector and both the electric power supply company and the end users are concerned about it [1]. The quality of power delivered to the consumers depends on the voltage and frequency ranges of the power. If there is any deviation in the voltage and frequency of the electric power delivered from that of the standard values then the quality of power delivered is affected.

Now-a-days with the advancement in technology there is a drastic improvement in the semi-conductor devices. With this development and advantages, the semi-conductor devices got a permanent place in the power sector helping to ease the control of overall system. Moreover, most of the loads are also semi-conductor based equipment. But the semi-conductor devices are non-linear in nature and draws non-linear current from the source. And also the semi-conductor devices are involved in power conversion, which is either AC to DC or from DC to AC. This power conversion contains lot of switching operations which may introduce discontinuity in the current. Due to this discontinuity and non-linearity, harmonics are present which affect the quality of power delivered to the end user. In order to maintain the quality of power delivered, the harmonics should be filtered out. Thus, a device named *Filter* is used which serves this purpose.

There are many filter topologies in the literature like- active, passive and hybrid. In this project the use of hybrid power filters for the improvement of electric power quality is studied and analyzed.

1.2 LITERATURE REVIEW

To overcome the problems caused by harmonics, filters are used. There are different filter topologies present in the literature for this purpose. At first passive filters are used but they are dependent heavily on the system parameters. They also have the problems of resonance with system impedance and are suitable for filtering out a particular frequency harmonics. Therefore, to overcome the problems of passive filters, active filters are used.

These are used since 1970's to compensate the reactive power, negative sequence currents.

The use of active power filters for power quality improvement is discussed in [2]. In this paper a review of active filter configuration for power quality improvement is presented along with control strategies. It is found that the active filters are facing some drawbacks when employed for power quality improvement. They are-

- High converter ratings are required
- Costlier when compared to its counterpart, passive filter
- Huge size
- Increased losses

Therefore, to overcome these drawbacks a hybrid power filter which is a combination of active and passive filters is proposed in [3]. This paper discusses how a combination of both active and passive filters is an economical solution for power quality improvement.

To enhance the characteristics of passive filter and also the system, the active filter should be controlled properly. There are different control techniques for this purpose. The main aim of any control technique is to make active filter inject a voltage in to the system that compensates the harmonics. To achieve this output voltage of the active filter is controlled such that it is equal to a pre-calculated reference value.

The active filter is controlled better with instantaneous reactive power theory. This is presented in [4] and it discusses the different control algorithms from the formulations of instantaneous reactive power theory. Finally it concludes that vectorial based theory yields better results with sinusoidal currents when compared with other algorithms.

The control of series active in conjunction with shunt passive filter using dual instantaneous reactive power vectorial theory is presented in [5]. In this paper the proposed theory is validated by simulating it in MATLAB SIMULINK environment. The proposed control strategy is simulated for both balance and unbalanced load conditions

1.3 RESEARCH MOTIVATION

1.3.1 Power Quality Problems:

The quality of power is affected when there is any deviation in the voltage, current or frequency [6]. The common problems that affect the sensitivity of the equipment are-

- Power Surges
- Transients
- Frequency Variation
- Electrical Line Noise
- Brownouts or Blackouts
- Power System Faults
- Improper grounding affect

The main affect caused by these problems is the production of harmonics. The presence of harmonics deteriorates the quality of power and may damage the end user equipment. These harmonics causes the heating of underground cables, insulation failure, reduces the life-time of the equipment, increases the losses etc.

1.3.2 Solutions to Power Quality Problems:

The most effective solution to improve the power quality is the use of filters to reduce harmonics. The basic idea of using a filter is explained in Fig. 1.1, where the filter injects a compensating current that compensates the harmonics in load current.

There are different filter topologies in the literature such as- active, passive, hybrid. The passive power filters are used to filter out a particular order harmonics and has the problem of parallel resonance. The other solution is the use of Active Power Filter (APF). There are different types of APF like series APF, shunt APF. The shunt APF is costly and is not used for large systems. The series APF works as a harmonic isolator and used to reduce the negative-sequence voltage [2]. There is another filter topology which is a combination of passive filter and APF known as *Hybrid Filter*.

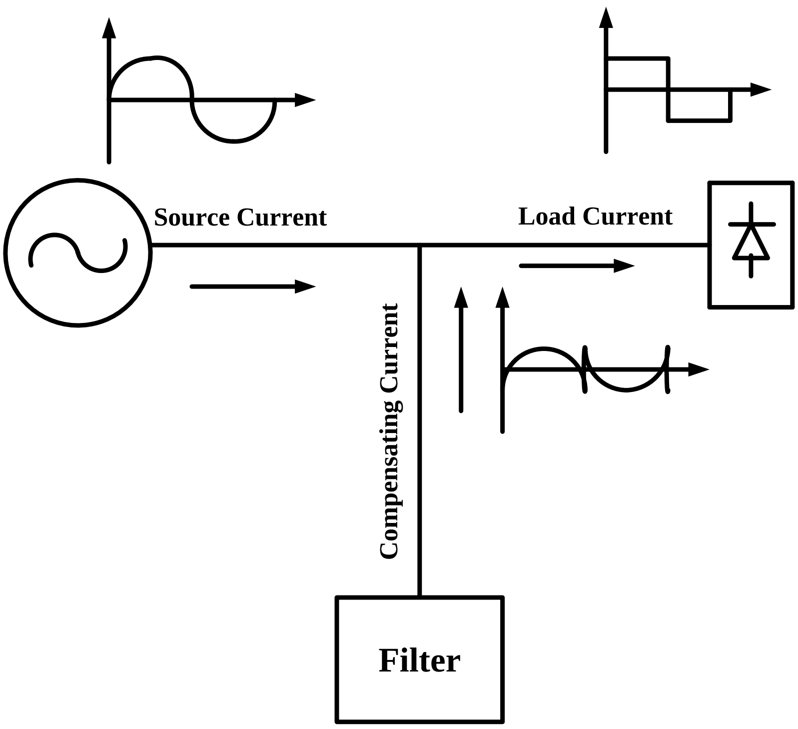


Fig.1.1 Basic Operation of Filter

1.3.3 Advantages of Hybrid Power Filter:

Hybrid Filter is a combination of series and shunt filters. Among the various available combinations, active-passive combination is effective as it has the advantages of both active and passive filters. The characteristics of the passive filter are improved [5], avoiding the problems of series and parallel resonances. The series APF with a shunt connected passive filter is widely used due to the above advantages.

Thus, the control of series APF with shunt connected passive filter is studied and analyzed in this project for the improvement of electric power quality.

1.4 THESIS OBJECTIVES:

The main objective of this project is to control the hybrid power filter such that the harmonics in the current waveform are reduced. The control algorithm has the following objectives-

- To control the voltage injected by APF such that it compensates the reactive power and load current harmonics
- To improve the passive filter performance

- To make the whole compensating equipment to act as linear, balanced, resistive load on the system

1.5 ORGANIZATION OF THESIS:

The whole thesis is organized into five chapters including introduction and each chapter is summarized below.

Chapter 2 deals with the types of filters available for harmonic reduction. It explains the merits and demerits of each type of filter with a circuit diagram.

Chapter 3 deals with the control of Hybrid Power Filter. It presents the design of the compensation strategy which generates a reference value for the output voltage of the APF that compensates the harmonics in the current waveform.

Chapter 4 deals with the simulation results and discussions. It presents the MATLAB SIMULINK simulation results of the proposed control strategy at different load conditions.

Chapter 5 deals with the conclusions work done and the future scope of the project followed by references.

Chapter2

TYPES OF FILTERS

Introduction

Filter classification

Chapter summary

2.1 INTRODUCTION

The electric power system is affected by various problems like transients, noise, voltage sag/swell, which leads to the production of harmonics and affect the quality of power delivered to the end user. The harmonics may exist in voltage or current waveforms which are the integral multiples of the fundamental frequency, which does not contribute for the active power delivery. Thus the response at these frequencies should be restricted from affecting the behavior of the system. To achieve this filter is used at the Point of Common Coupling (PCC) where the load is connected to the supply. This filter filters out the harmonics and improves the performance of the system. There are different types of filters available for this purpose. Each of them is explained in detail in this chapter.

2.2 FILTER CLASSIFICATION

The different filters present in the literature are classified into three basic types. They are Active Filters and Passive Filters and Hybrid filter. Each type has its own sub classification. Fig. 2.1 shows the detailed classification of the filters.

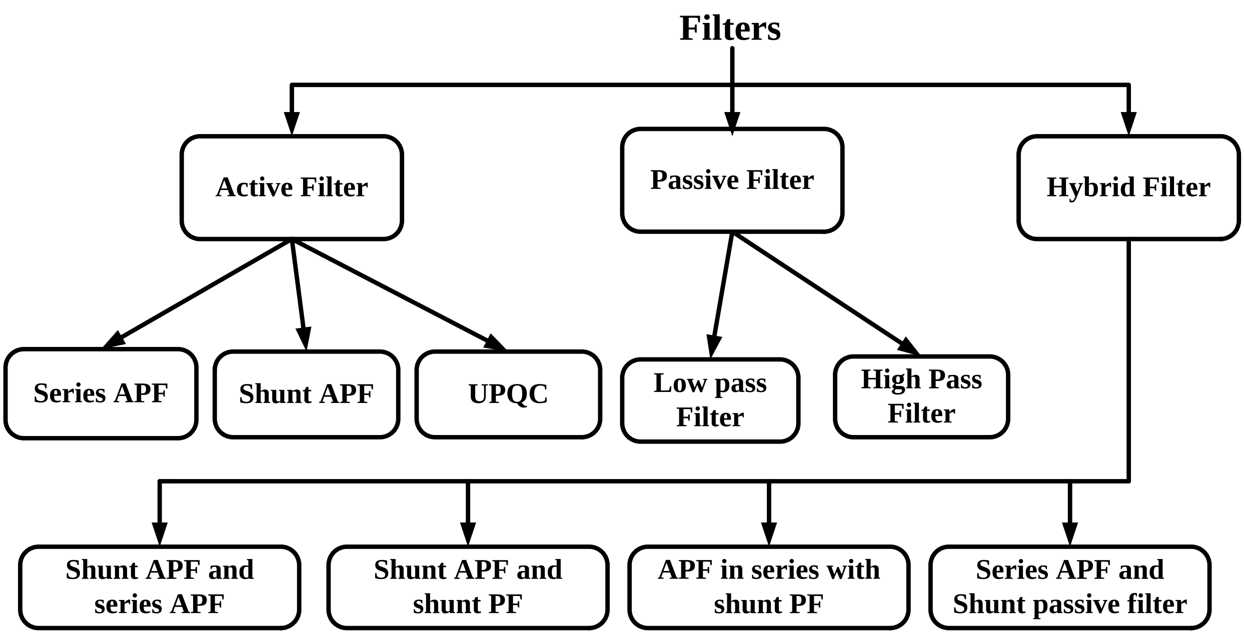


Figure2.1 Classification of Filters

2.2.1 Passive Power Filters:

These filters consist of passive elements like- capacitor, inductor and resistor. These are widely used because of their low cost and ease of control. The passive filters also provide reactive power apart from filtering the harmonics. The performance of these filters is heavily dependent on the system impedance. These are again classified into two types- low pass and high pass.

A. Low Pass Filter:

The low pass filter is a tuned LC circuit that is tuned to provide low impedance for a particular harmonic current. In addition these filters are also used for power factor correction. In power system network these are generally used to filter 5^{th} and 7^{th} order harmonics. The line diagram of the low pass filter is shown in Fig. 2.2.

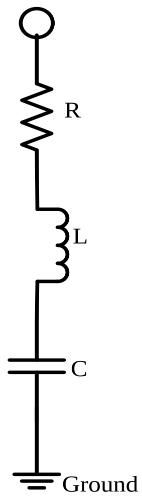


Figure2.2 Low Pass Filter

B. High Pass Filter:

The high pass filters are also made of passive elements like inductor and capacitor but show low impedance for harmonic current above a particular corner frequency. All the harmonics present above that corner frequency are filtered using this filter. This filter is again of many types like single-order, two-order, third-order etc., based on the number of passive filters used in it. Among them the two-order filter is widely used. Fig. 2.3 shows the line diagram of a high pass filter.

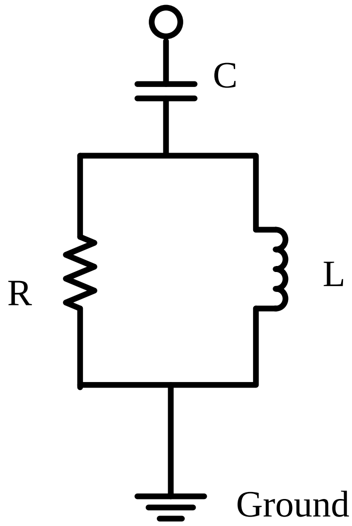


Figure2.3 High Pass Filter

But there are some disadvantages with passive filter, like-

- The filter characteristics has strong dependence on the system impedance
- Possibility of over load in the passive filter because of harmonic current circulation generating from power electronic loads
- The change of the load impedance can detune the filter, so it is not suitable for variable loads
- The problem of series and/or parallel resonances can be originated which causes instable operation
- Limited operation, that is used to eliminate either a particular order or fewer harmonics
- Component aging

Because of the above disadvantages the passive filters cannot provide an effective solution to enhance the quality of the power system. Thus, the active power filters are employed to overcome the above drawback.

2.2.2 Active Power Filters (APF):

To overcome the drawback of passive filter, active compensation known as Active Power Filter is used recently. The APF is a Voltage Source Inverter (VSI) which injects the compensating current or voltage based on the network configuration. It was proposed around 1970. But the recent advancement in power electronics technology [2], along with the theory of instantaneous active and reactive power which was presented in 1983, APF's are an up-to-date solution with fast switching devices, low power loss and fast digital processing devices at an affordable price. Depending on the circuit configuration and function, APF's are divided into three types and each one is explained in detail below.

A. Shunt Active Power Filter:

The voltage sourced inverter based Shunt APF is similar to STATCOM. It is connected in shunt at the PCC. It injects the current which is equal and opposite to the harmonic current. It acts as a current source injecting harmonics and is suitable for any type of load. It also helps in improving the load power factor. The circuit diagram of the power system with shunt connected APF is shown in Fig. 2.4. The cost of these filters is relatively higher and so not preferred for large scale systems.

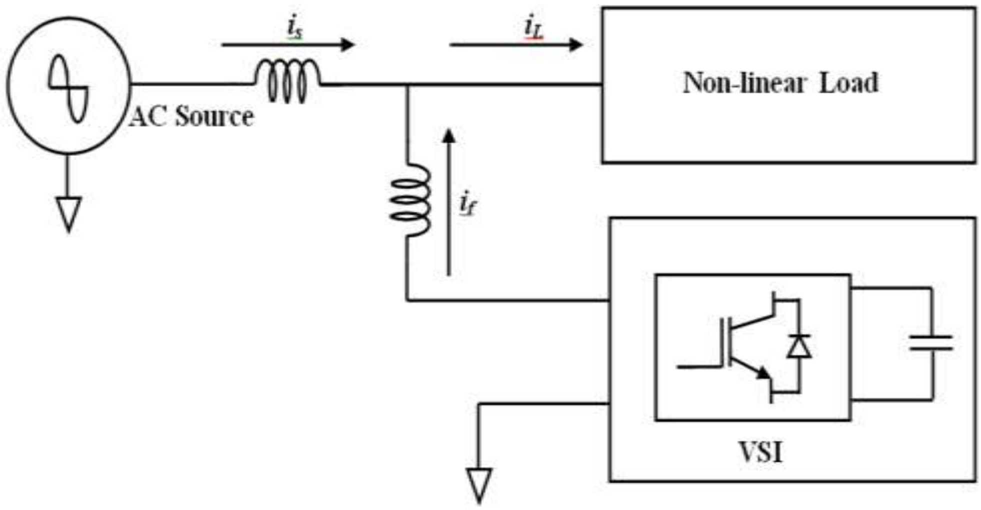


Figure2.4 Circuit Diagram of Shunt active power filter

B. Series Active Power Filter:

As the name indicates, these filters are connected in series with the line through a matching transformer. This filter injects the compensating voltage in series with the supply voltage. Thus, it acts as a voltage source which can be controlled to compensate the voltage sag/swell. These filters have their application mainly where the load contains voltage sensitive devices. The circuit diagram of the power system with series connected APF is shown in Fig. 2.5. These filters are not used practically since they are required to handle high current ratings which increase the size of the filter as well as the losses occurring in the filter.

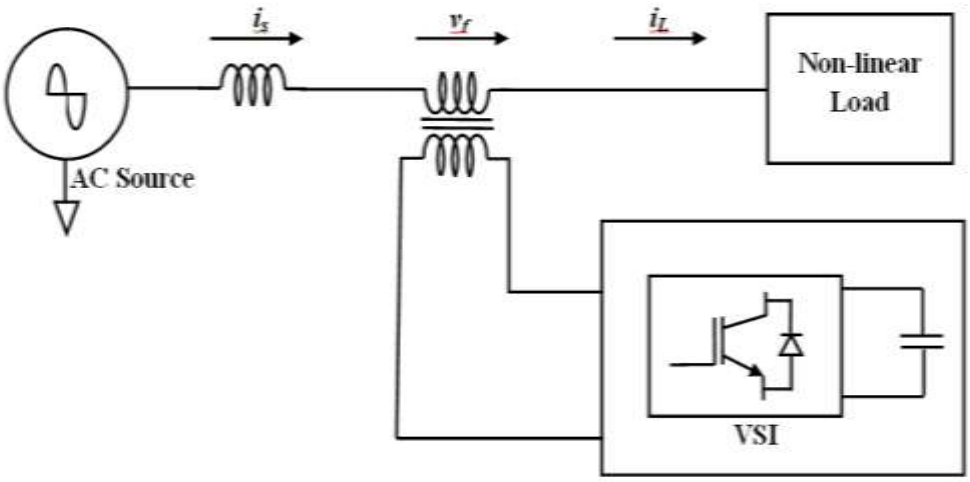


Figure2.5 Circuit Diagram of Series active power filter

C. Unified Power Quality Conditioner (UPQC):

The UPQC is a combination of series and shunt active power filters. It has the advantage of both series APF and shunt APF. That means, it compensates both the voltage and current harmonics. Therefore, this filter can compensate almost all types of power quality problems faced by a power system network [7]. The circuit diagram of power system with UPQC is shown in Fig. 2.6.

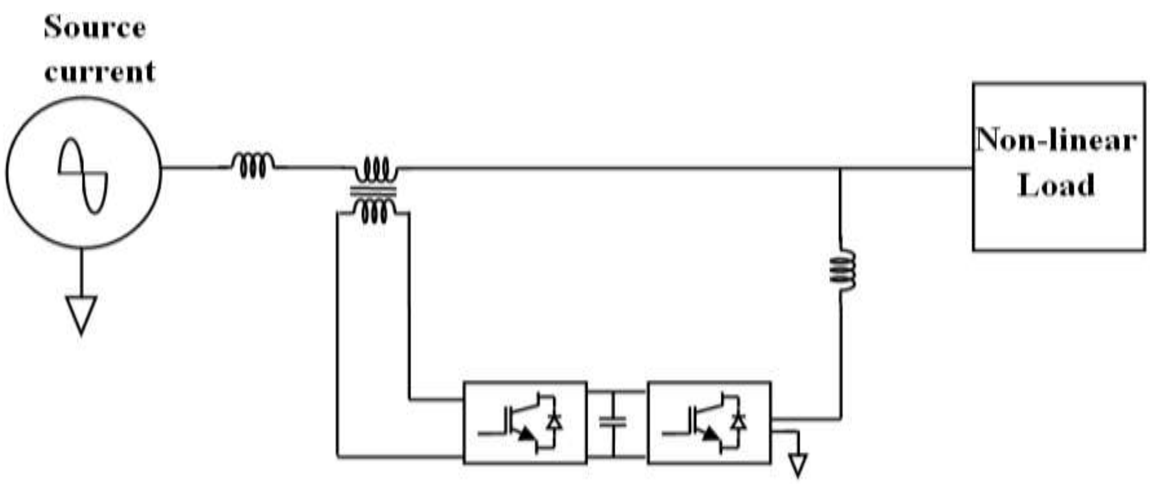


Figure2.6 Circuit Diagram with UPQC

2.2.3 Hybrid Power Filters:

The active power filters are better solution for power quality improvement but they require high converter ratings. So to overcome the above drawback, hybrid power filters are designed. The hybrid power filters are the combination of both active and passive power filters. They have the advantage of both active and passive filters. There are different hybrid filters based on the circuit combination and arrangement. They are-

- Shunt Active Power Filter and Series Active Power Filter
- Shunt Active Power Filter and Shunt Passive Filter
- Active Power Filter in series with Shunt Passive Filter
- Series Active Power Filter with Shunt Passive Filter

Each filter configuration is explained below with their merits and demerits.

A. Shunt APF and Series APF:

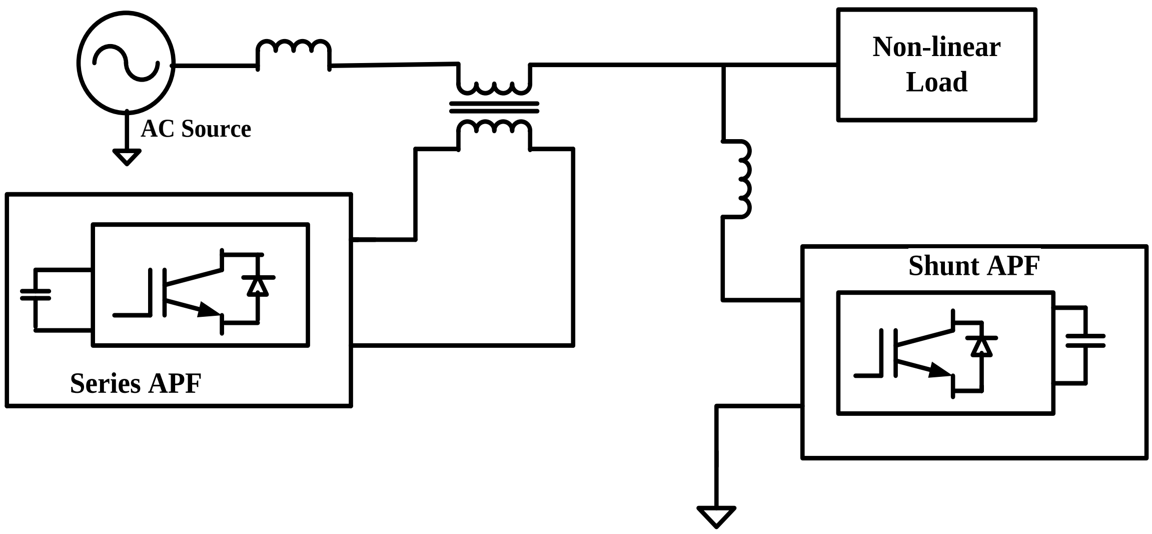


Figure2.7 Shunt APF and Series APF Combination

This filter combination has the advantage of both series connected APF i.e., elimination of voltage harmonics and that of shunt connected APF of eliminating current harmonics. The circuit diagram is shown in Fig. 2.7. This combination finds its application in Flexible AC Transmission Systems (FACTS). But the control of APF is complex and this combination involves two APF and hence the control of this filter configuration is even more complex. Thus, this filter combination is not used widely.

B. Shunt APF and Shunt Passive Filter:

The power rating of the APF depend on the order of frequencies it is filtering out. Thus, an APF used for filtering out low order harmonics have low power rating with reduced size and cost. This logic is used in designing this filter combination.

The shunt connected APF filters out the low order current harmonics while the shunt connected passive filter is designed to filter out the higher order harmonics. The circuit configuration of this filter topology is shown in Fig. 2.8.

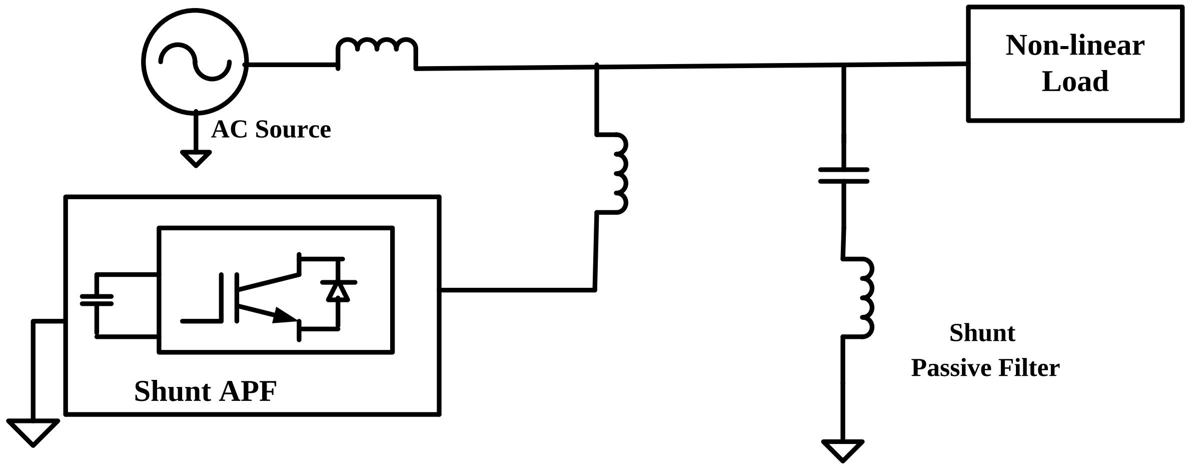


Figure2.8 Shunt APF and Shunt Passive Filter Combination

But the main disadvantage of this filter configuration is it cannot be suited for variable loading conditions. Since, the passive filter can be tuned only for a specific predetermined harmonic.

C. APF in Series with Shunt Passive Filter:

In this filter configuration, the Active Power Filter is connected in series with a Shunt connected Passive Filter. The circuit diagram of this filter configuration is shown in Fig. 2.9. The advantage of this configuration is that the passive filter reduces the stress on the power electronic switches present in the APF. This filter has its application in medium to high voltage ranges.

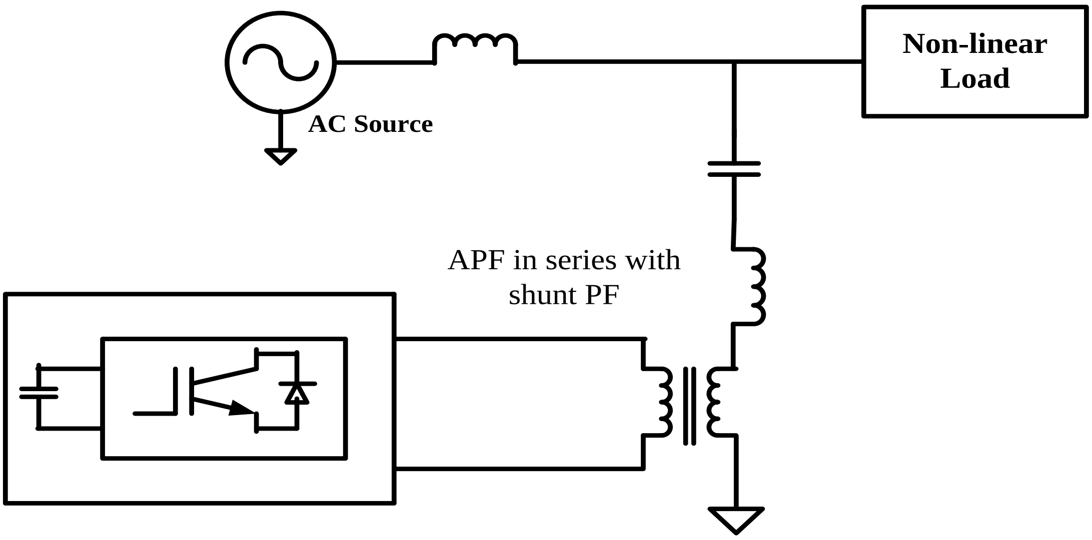


Figure2.9 APF in series with Shunt Connected Passive Filter

D. Series APF with Shunt Connected Passive Filter:

The Series APF and Shunt APF combination seen in Fig. 2.7 has the problem of complex control strategy. To overcome this drawback, the shunt APF is replaced by a shunt connected passive filter. The passive power filter does not require any additional control circuit and the cost is also less. This filter combination is shown in Fig. 2.10.

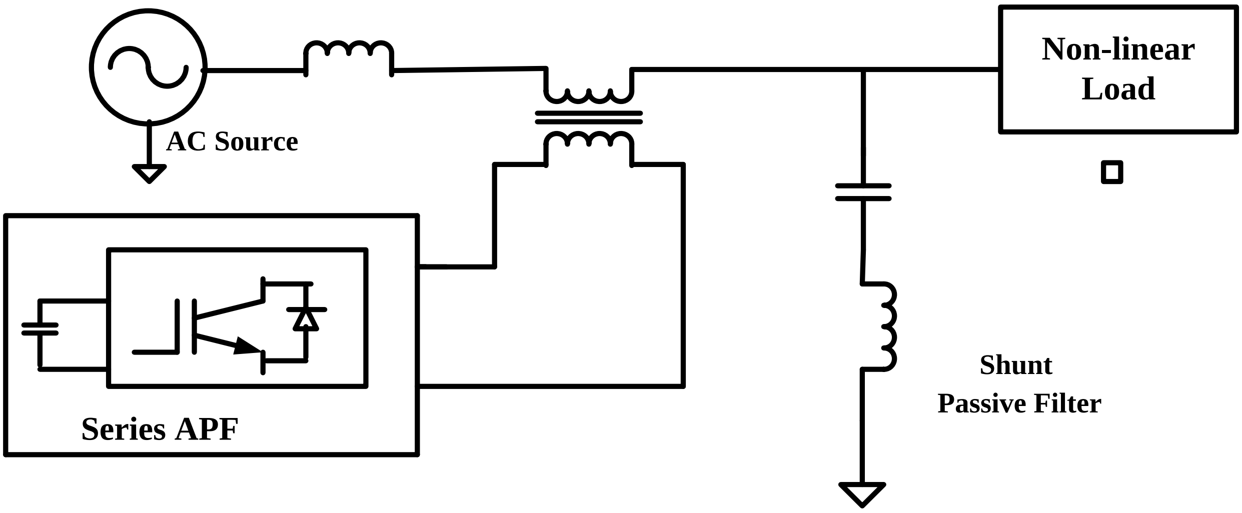


Figure2.10 Series APF with Shunt Connected Passive Filter

Here the series connected APF provides low impedance (almost zero) for low frequency components whereas the shunt connected APF provides less impedance for high frequency components and filters out all higher order harmonics. So this filter configuration is the most beneficial of all others and has the advantage of reducing both current and voltage harmonics. Thus [5], in this project this filter configuration is used for the improvement of electric power quality.

2.3 CHAPTER SUMMARY

This chapter deals with different filter topologies that are used for the improvement of electric power quality. It explains in detail each filter configuration along with their merits and demerits. From the above discussion, it is clear that the passive filters are low cost solution but are not effective. The active power filters can overcome the drawbacks of passive filter but their control is complex and difficult to implement. Thus, a hybrid filter is chosen which works effectively to the quality of power. Among the different available hybrid filter configurations, the series APF with a shunt connected passive filter best serves the purpose.

Chapter3

CONTROL OF HYBRID POWER FILTER FOR POWER QUALITY IMPROVEMENT

Introduction

Design of series active power filter

Modeling of series active power filter

Control strategy

Chapter summary

3.1 INTRODUCTION

The filter is used to reduce the harmonics and improve the power quality. The filter that is connected to the system should be controlled effectively such that its response characteristics are as desired. Among the different available filter configurations, hybrid power filter with series APF and a parallel passive filter is used in this project. The control circuit of the series connected APF is designed such way that the voltage injected by the APF compensates the harmonics and also enhances the performance of the shunt connected passive filter. The control strategy of the hybrid power filter is explained in detail in this chapter.

3.2 DESIGN OF SERIES ACTIVE POWER FILTER

The series APF used for the power quality improvement is realized as a Voltage Source Inverter (VSI) [8]. It can be a three-phase VSI or three single-phase VSI's can also be used. The VSI is connected in series with the source impedance through a matching transformer. The circuit diagram is shown in Fig. 3.1. A capacitor is used at the input if the VSI to provide constant input voltage to VSI.

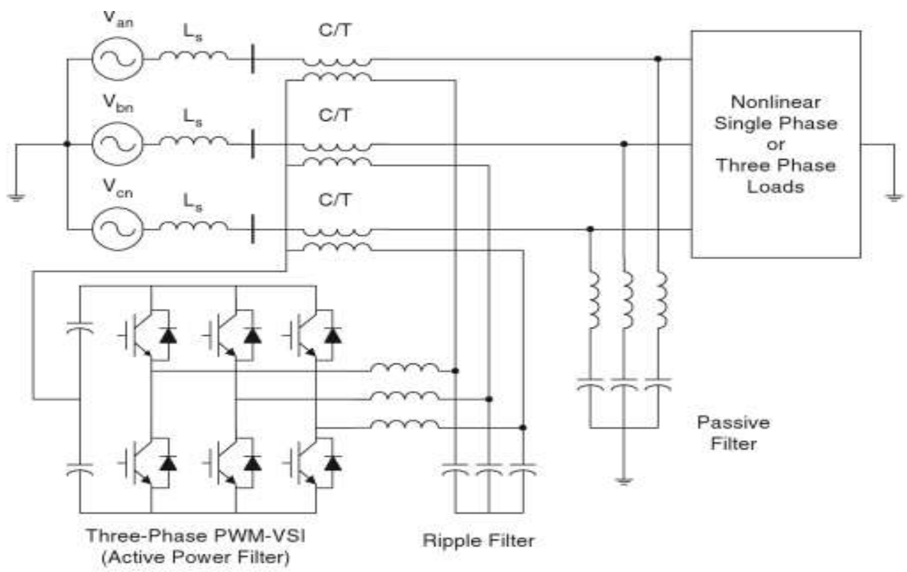


Figure3.1 Overall Circuit Diagram of the System with Hybrid Filter

A passive filter is also connected at the PCC. This filter is tuned to eliminate higher order harmonics [9] [10]. In certain cases there may be two or more LC branches tuned to eliminate specific order harmonics (especially 5^{th} and 7^{th}). A ripple filter is used in series with VSI. The filter parameters are selected such that they do not exceed the transformer burden. The design criteria is [5]-

- $X_{Crf} << X_{Lrf}$, such that at switching frequency the inverter output voltage drops across L_{rf}
- $X_{Crf} << Z_S + Z_F$, to make the voltage divide between L_{rf} and C_{rf}

Thus, with an efficient control strategy, the APF compensates the voltage unbalances and distortion. The control strategy is designed such that the series APF together with the passive filter act as a balanced resistive load on the overall system. In a four-wire system, the harmonic currents circulated in the neutral wire are also reduced due to series APF.

3.3 MODELING OF SERIES ACTIVE POWER FILTER

The modeling of the series Active Power Filter is necessary in order to control the filter. In this project, the modeling of the series APF which is nothing but a three-phase VSI is carried out in 2-ϕ stationary reference frame (α-β). Thus, the three phase quantities, voltage and current vectors, are transformed into α-β co-ordinates by using Clarke's Transformation [11] [12].

In a 3-ϕ three-wire system the voltage vector is represented as-

$$V = [V_a \quad V_b \quad V_c]^T \tag{3.1}$$

The current vector in three-phase system is given as-

$$i = [i_a \quad i_b \quad i_c]^T \tag{3.2}$$

Now these voltage and current vectors are changed into two-phase system using the transformation matrix-

Therefore, the instantaneous value of real power in the *0-α-β* frame can be calculated as-

$$p_{3\emptyset}(t) = v_\alpha i_\alpha + v_\beta i_\beta + v_0 i_0 \tag{3.3}$$

Here in equation (3.3) v_0, i_0 represent the zero sequence voltage and zero sequence current respectively. Their product gives the zero sequence power denoted as p_0. Thus, the equation (3.3) can be written as-

$$p_{3\emptyset}(t) = p + p_0 \tag{3.4}$$

Here P represents the instantaneous real power and is written as-

$$p = v_\alpha i_\alpha + v_\beta i_\beta \tag{3.5}$$

The power can be represented in vectorial form using dot product. Hence the active power when represented in vector form can be written as-

$$p = i_{\alpha\beta}^T v_{\alpha\beta} \tag{3.6}$$

Here $i_{\alpha\beta}^T$ the transposed current vector in α-β coordinates and $v_{\alpha\beta}$ is the voltage vector in α-β coordinates and are given by equations (3.7) and (3.8) respectively.

$$i_{\alpha\beta} = [i_\alpha \quad i_\beta]^T \tag{3.7}$$

$$v_{\alpha\beta} = [v_\alpha \quad v_\beta]^T \tag{3.8}$$

In a three-phase three-wire system, the zero sequence power will be zero and hence the term p_0 in equation (3.4) can be neglected. The instantaneous imaginary power can be obtained by the equation (3.9) as-

$$q = v_\alpha i_\beta - v_\beta i_\alpha \tag{3.9}$$

The above equation can be expressed in vector form as-

$$q = i_{\alpha\beta\perp}^T v_{\alpha\beta} \tag{3.10}$$

Where $i_{\alpha\beta\perp}^T$ is the transposed current vector perpendicular to $i_{\alpha\beta}$ and is giving by equation (3.11) as-

$$i_{\alpha\beta\perp} = [i_\beta \quad -i_\alpha]^T \tag{3.11}$$

When the instantaneous real and reactive power in equations (3.6) and (3.10) are expressed in matrix form then the matrix equation is-

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} i_{\alpha\beta}^T \\ i_{\alpha\beta\perp}^T \end{bmatrix} v_{\alpha\beta} \tag{3.12}$$

The voltage vector can be decomposed in its orthogonal projection on the current vector axis as shown in Fig. 3.2.

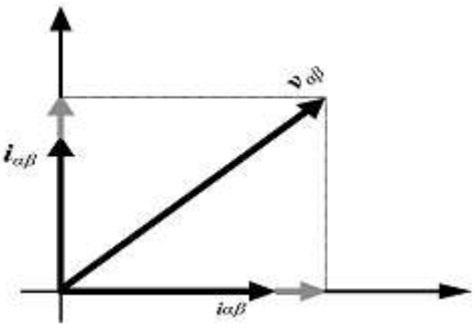


Figure3.2 Voltage Vector Decomposition

With the help of the current vectors and the real and imaginary instantaneous power, the voltage vector can be written as-

$$v_{\alpha\beta} = \frac{p}{i_{\alpha\beta}^2} i_{\alpha\beta} + \frac{q}{i_{\alpha\beta}^2} i_{\alpha\beta\perp} \tag{3.13}$$

In case of three-phase four-wire system, there will be an extra term in the above equation corresponding to the zero sequence current component.

3.4 CONTROL STRATEGY

The series APF should be controlled such that the voltage injected by it should compensate the harmonics present in the system and should help in improving the quality of power. To achieve the above purpose, the output voltage of the APF should be controlled.

For this to happen, at first a reference voltage is generated which when injected by APF will serve the desired purpose. Then the actual output voltage of the series connected APF is controlled using a PI controller such that the actual output voltage generated is equal to the reference value. The overall control strategy is shown by the flow chart given in Fig. 3.3.

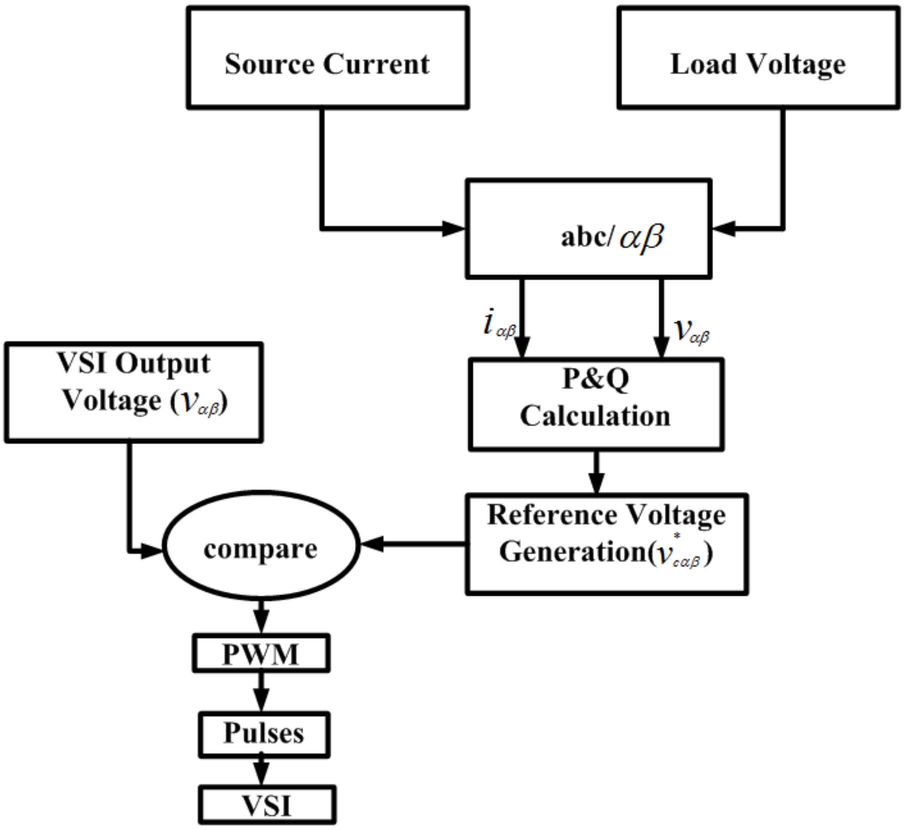


Figure3.3 Flow Chart of Control Strategy

3.4.1 Compensation Strategy:

The compensation strategy to compensate the harmonics is designed based on "Dual Instantaneous Reactive Power Theory". In general, the power company tries to generate electric power at sinusoidal and balanced voltage. To achieve this condition, the load current at the Point of Common Coupling (PCC) should be co-linear with the supply voltage. This condition is satisfied if the load is a linear, balanced and resistive. This condition is expressed in equation form as-

$$v = R_e i \tag{3.14}$$

Where R_e is the equivalent resistance.

Thus, the average power supplied by the source is given as-

$$P_s = I^2 R_e \tag{3.15}$$

In case of unbalanced loads, where harmonics exist, only the fundamental component of the current helps in supplying the active power to the load. So the current in the equation (3.15) is only the fundamental component and is represented as I_1.

The load power is the summation of the source power and the compensator power. But the power exchange by the compensator should be null. So the load power is equal to the source power.

Therefore, the equivalent resistance is obtained as-

$$R_e = \frac{p_L}{I_1^2} \tag{3.16}$$

Thus, the voltage at the PCC in α-β co-ordinates is obtained as-

$$v_{PCC\alpha\beta} = R_e i_{\alpha\beta} \tag{3.17}$$

By substituting equation (3.16) in (3.17) the voltage at PCC is obtained as-

$$v_{pcc\alpha\beta} = \frac{p_L}{I_1^2} i_{\alpha\beta} \tag{3.18}$$

From equation (3.13) the load voltage can be written as-

$$v_{L\alpha\beta} = \frac{p_L}{i_{\alpha\beta}^2} i_{\alpha\beta} + \frac{q_L}{i_{\alpha\beta}^2} i_{\alpha\beta\perp} \tag{3.19}$$

Thus, the compensating voltage of the series APF is obtained as-

$$v_{C\alpha\beta}^* = v_{pcc\alpha\beta} - v_{L\alpha\beta} \tag{3.20}$$

From equations (3.18) and (3.19) the equation (3.20) is modified as-

$$v_{C\alpha\beta}^* = \left(\frac{p_L}{I_1^2} - \frac{q_L}{i_{\alpha\beta}^2}\right) i_{\alpha\beta} - \frac{q_L}{i_{\alpha\beta}^2} i_{\alpha\beta\perp} \tag{3.21}$$

This is the reference value of the voltage that is to be supplied by the APF in order to make the set load and compensating equipment to act as resistive load.

3.4.2 Reference Vector Generation:

To control the series connected APF the reference vector should be generated and compared with the actual voltage vector [1]. The reference voltage vector given by equation (3.21) is generated by the following control block shown in Fig. 3.4. The fundamental current component calculation is shown in Fig. 3.5. The fundamental component calculation needs the grid voltage angle to calculate the value. The grid voltage angle necessary for this calculation is extracted by using a Phased Lock Loop (PLL).

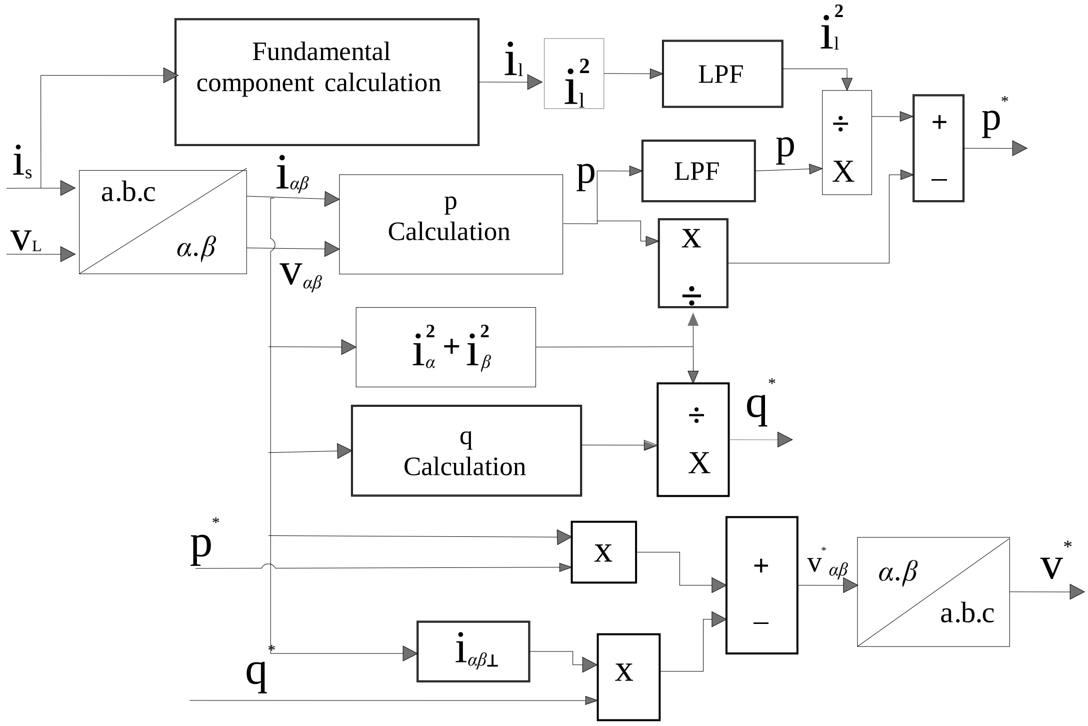


Figure3.4 Control Block to Generate Reference Vector

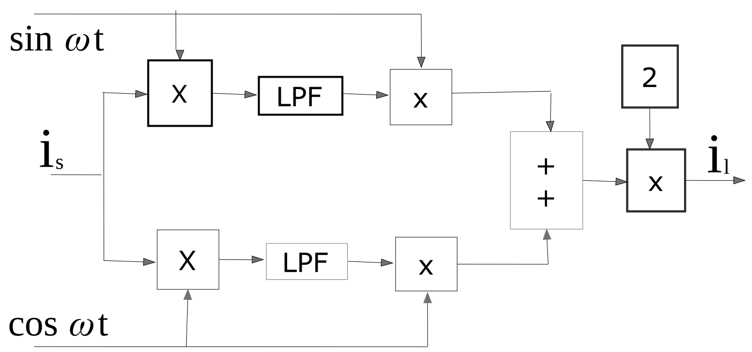


Figure3.5 Fundamental Component Calculation

A Low pass filter (LPF) is used in the fundamental calculation block to filter out the harmonics and extract the fundamental component. A comparison is made between the actual and reference values of the output voltage of APF. The error is passed through a PI controller. The gain values of the controller are tuned in such a way that the error is zero and the actual value matches almost with the reference value. If this condition is achieved perfectly then the series APF improves the quality of power generated to the load by filtering out the harmonics and thus improving the performance of the system.

3.5 CHAPTER SUMMARY

This chapter deals with the control of the series Active Power Filter. It explains how the APF is controlled such that the power quality is improved. The mathematical model of the series APF is derived and the generation of the reference voltage vector is explained in detail. The control algorithm is based on Dual Instantaneous Electric Power Vectorial Theory. The overall control algorithm is designed such that the compensating equipment (filter) and the load together act as a resistive load on the supply system.

Chapter4

SIMULATION RESULTS AND DISCUSSIONS

Introduction

Simulation results with balanced load

Simulation results with unbalanced load

Chapter summary

4.1 INTRODUCTION

The proposed control strategy is simulated in MATLAB SIMULINK environment to check the performance of the control strategy in improving the system behavior. The simulation is carried under two different load conditions-

- Non-linear Balanced Load
- Non-linear Unbalanced Load

The performance of the system with the proposed control strategy under different load conditions is discussed in detail in the following section.

4.2 SIMULATION RESULTS WITH BALANCED LOAD

The proposed control strategy is simulated with a non-linear balanced load and the performance of the system is analyzed. The system data is given in Table-I.

TABLE-I SYSTEM PARAMETERS

System Parameter	**Value**
Voltage	100 V
Switching Frequency	20 KHz
Source Inductance	5.8 mH
Source Resistance	3.6Ω
Turns Ratio of Coupling Transformer	1:1

The series APF is connected through a coupling transformer whose turn’s ratio is 1:1. A passive filter is connected at PCC to eliminate fifth and seventh order harmonics. Also a ripple filter is also connected at the output of the VSI. The values of these filters along with load values are given in Table-II.

TABLE-II FILTER PARAMETERS

Filter Parameter	**Value**
L_5	13.5 mH
C_5	30 µF
L_7	6.75 mH
C_7	30 µF
L_r	13.5 mH
C_r	50 µF
R_L	25 Ω
L_L	55 mH
C_L	2200 µF

The filter impedance should be less than the system impedance for effective filtering.The simulation is carried out under three conditions- with the actual system parameters, by increasing the impedance of LC filter more than source impedance and by changing the load values. Also the simulation is carried out with different loads- RL and RC.

4.2.1 With the Actual System Parameters:

With the system parameters in table-I, the proposed control strategy is simulated and the circuit diagrams with RL and RC loads are shown in Fig. 4.1 and Fig. 4.2 respectively. The MATLAB SIMULINK results are presented in Fig. 4.3. Fig. 4.3(a) shows the load current which is nothing but the source current of phase- ‘a’ without any compensation. The THD of this current is shown in Fig. 4.3(b) which is too high (27.75%) exceeding the IEEE standards. To filter the harmonics at first only the passive filter is connected and the source current waveform under this condition is shown in Fig. 4.3(c). When both active and passive filters are connected together, the harmonics are still reduced and the source current is almost sinusoidal as shown in Fig. 4.3(d). Now the THD of the current is very less (1.3%) and the harmonic analysis is shown in Fig. 4.3(e). The use of active power filter increases the performance of the system and the overall power factor is also improved. In addition, the characteristics of the passive filter are also improved and the 5^{th} and 7^{th} order harmonics are greatly reduced. The corresponding simulation results with RC load is shown in Fig. 4.4.

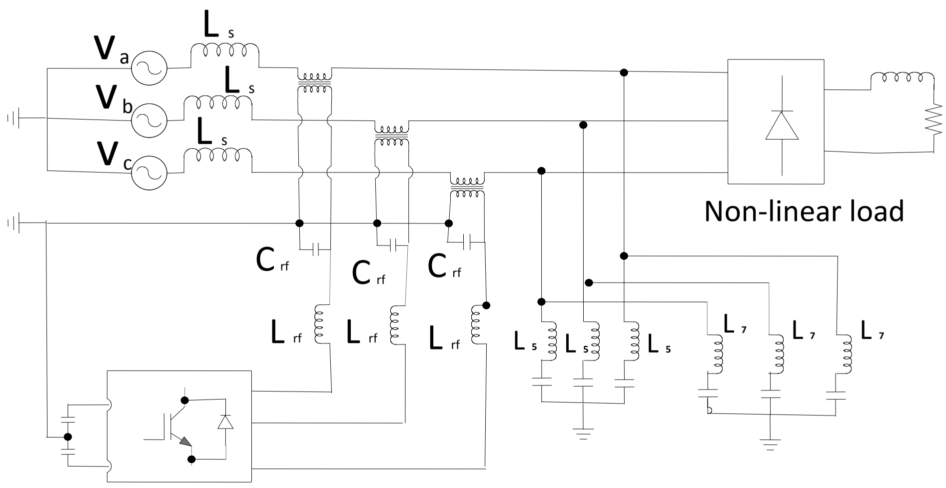


Figure4.1 Simulation Diagram with RL-Load

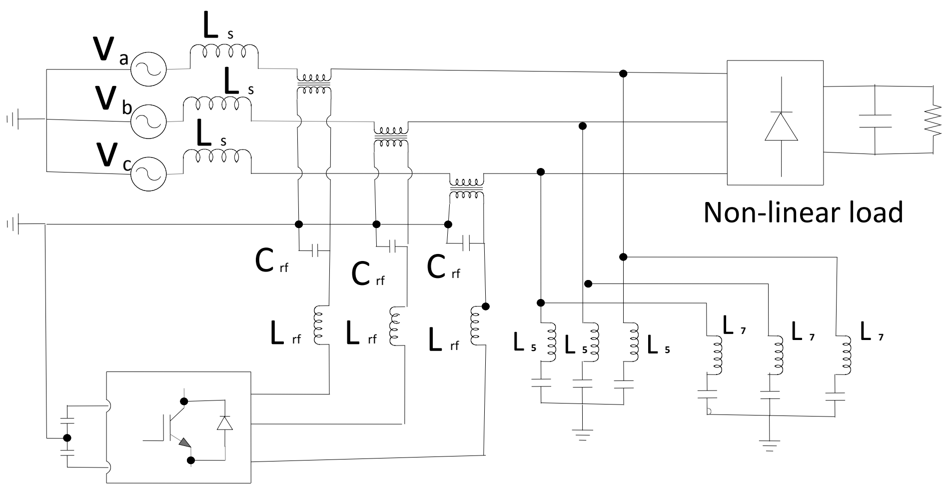
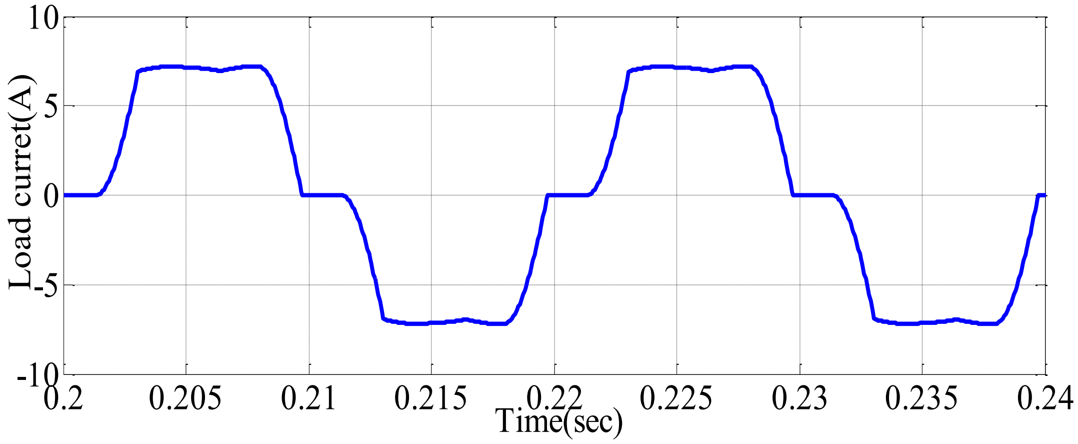
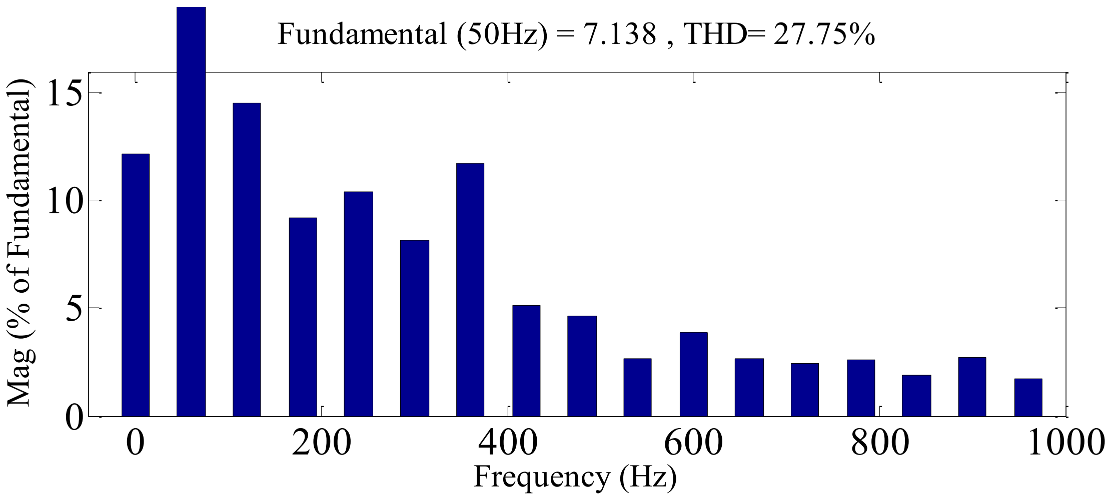


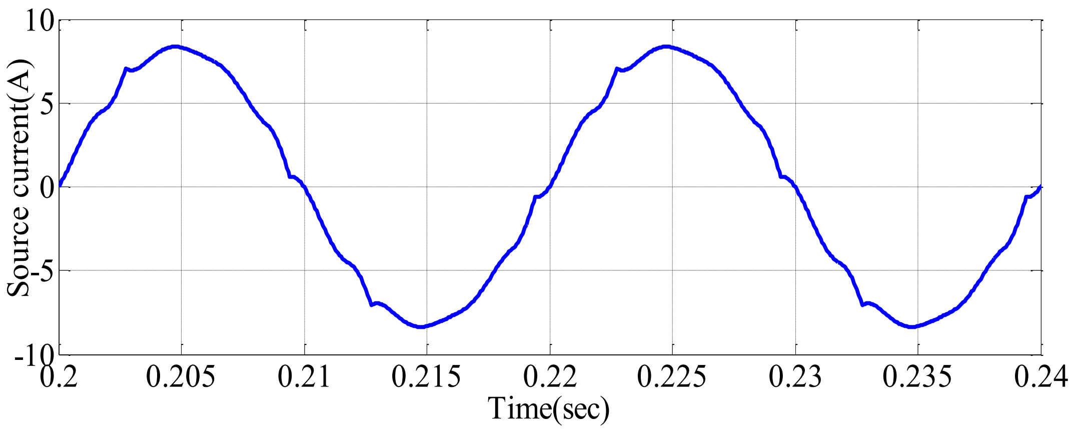
Figure4.2 Simulation Diagram with RC-Load


10
5
0
-5
-10
Load curret(A)
0.2
0.205
0.21
0.215
0.22
0.225
0.23
0.235
0.24
Time(sec)

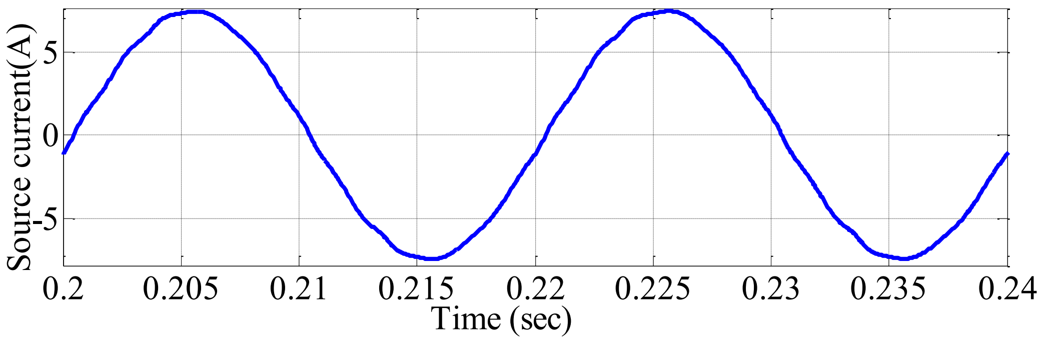
(a)


Fundamental (50Hz) = 7.138 , THD= 27.75%
15
10
5
0
Mag (% of Fundamental)
0
200
400
600
800
1000
Frequency (Hz)

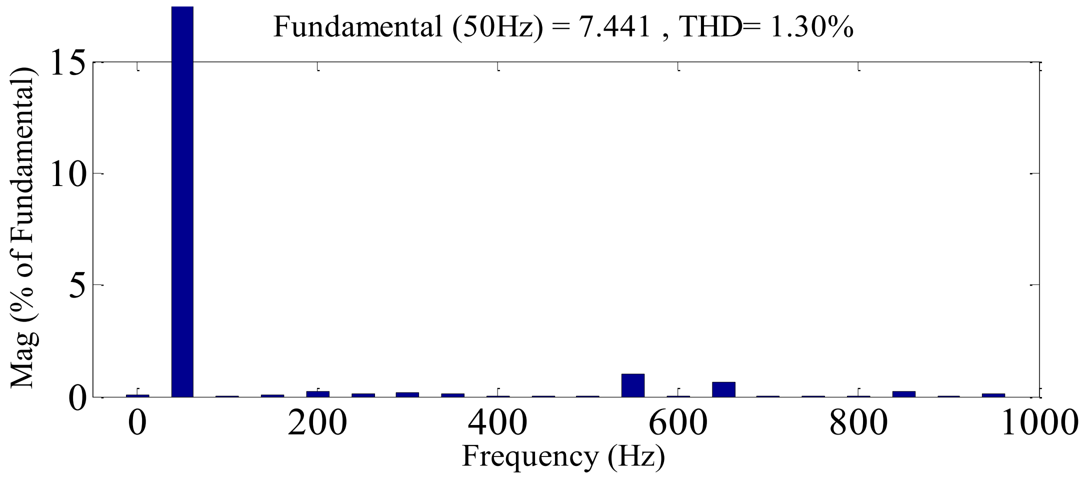
(b)


10
5
0
-5
-10
Source current(A)
0.2
0.205
0.21
0.215
0.22
0.225
0.23
0.235
0.24
Time(sec)

(c)

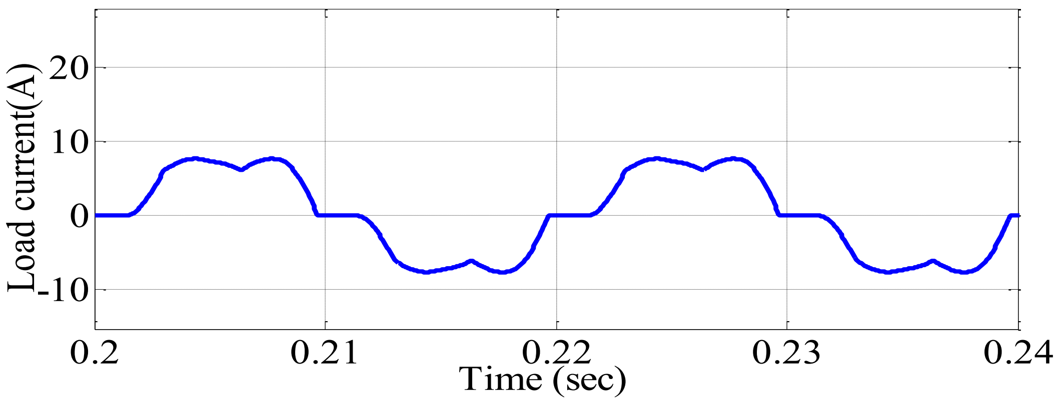


(d)

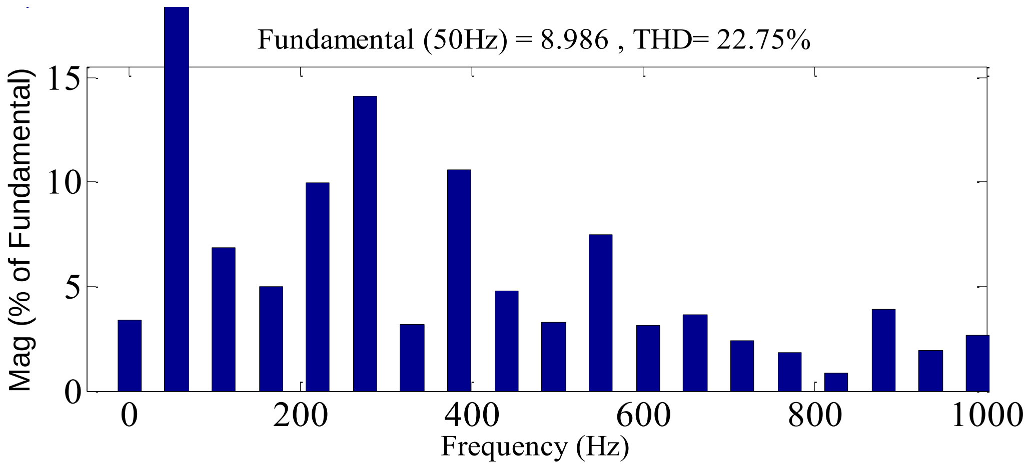


(e)

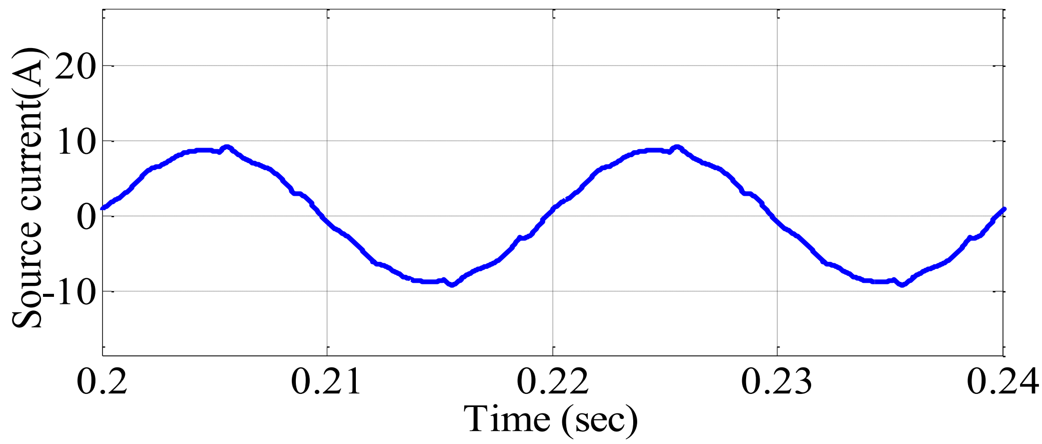
Figure4.3Simulation Results with RL Load (a) Load current without compensation (b) THD of load current (c) Source current when passive filter is connected (d) Source current when both passive and active filter are connected (e) THD of source current when both filters are connected.



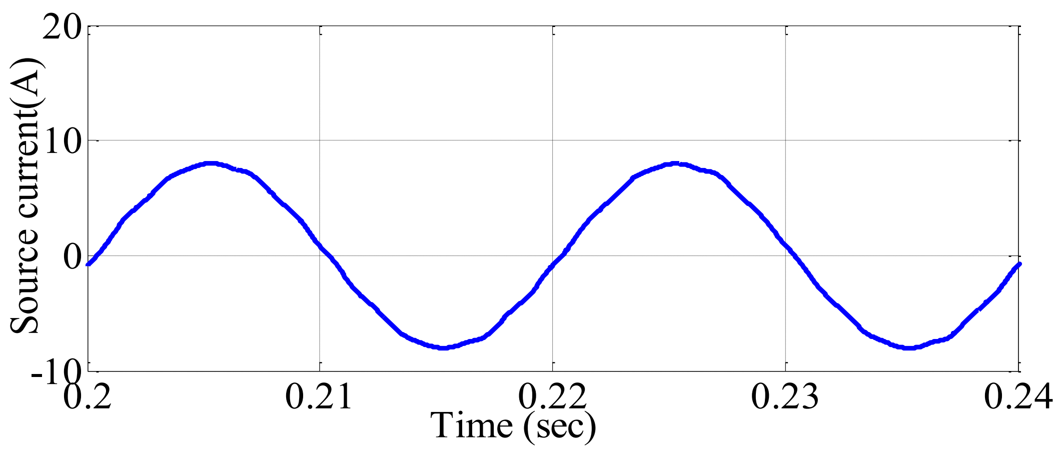
(a)


Fundamental (50Hz) = 8.986 , THD= 22.75%
Mag (% of Fundamental)
15
10
5
0
0
200
400
600
800
1000
Frequency (Hz)

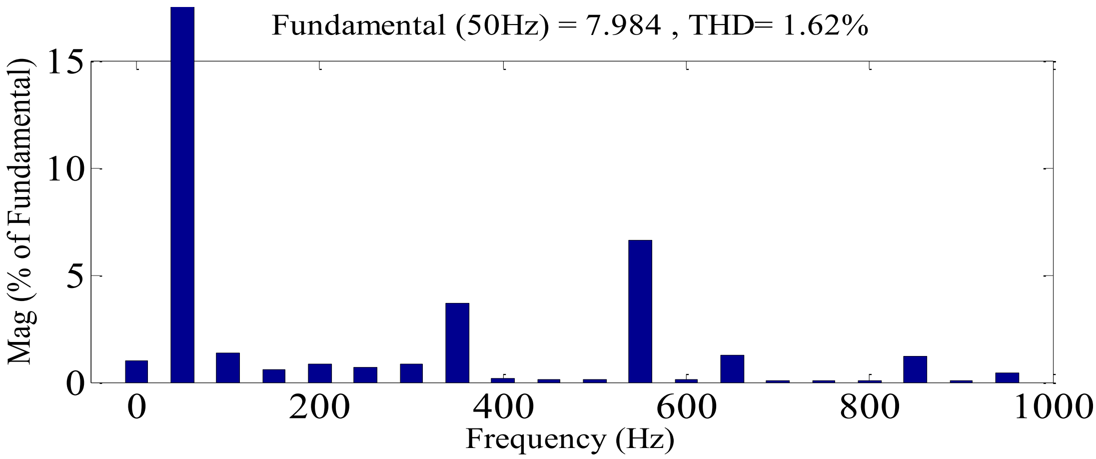
(b)


Source current(A)
20
10
0
-10
0.2
0.21
0.22
0.23
0.24
Time (sec)

(c)


Source current(A)
20
10
0
-10
0.2
0.21
0.22
0.23
0.24
Time (sec)

(d)

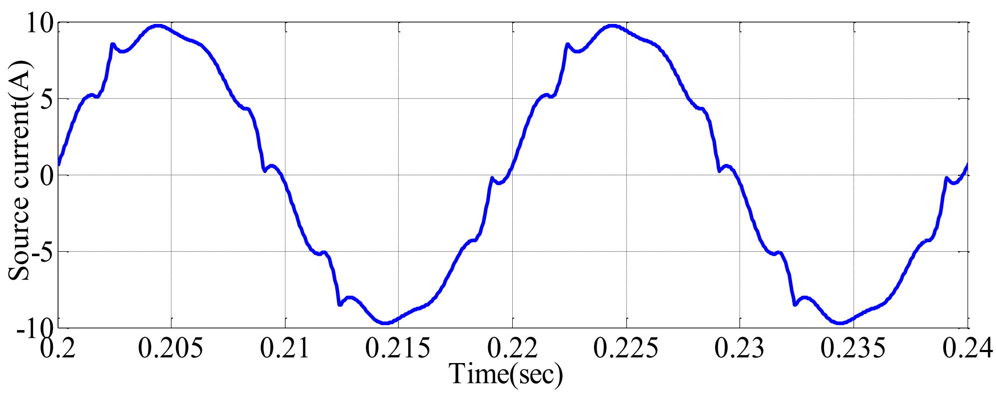


(e)

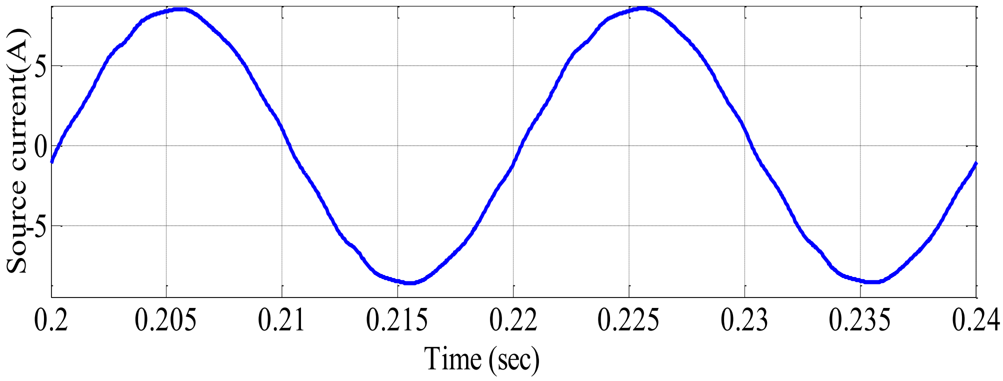
Figure4.4 Simulation Results with RC Load (a) Load current without compensation (b) THD of Load current without compensation (c) Source current when passive filter is connected (d) Source current when both passive and active filter are connected (e)THD of) Source current when both passive and active filter are connected

4.2.2 When the Source Impedance is changed:

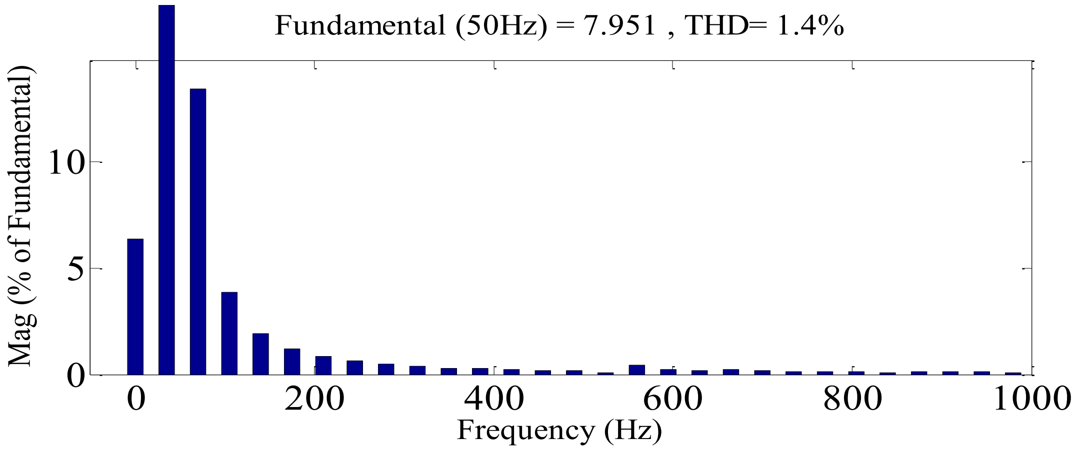
To study the performance of the system when the source impedance is less than passive filter impedance, this simulation is carried out. The source impedance of the system is reduced from its previous value given in Table-I and the new values are- L_s = 2.34 mH and R_s = 1.3 Ω. The simulation results are presented in Fig. 4.5 and Fig. 4.6 with RL and RC loads respectively.



(a)

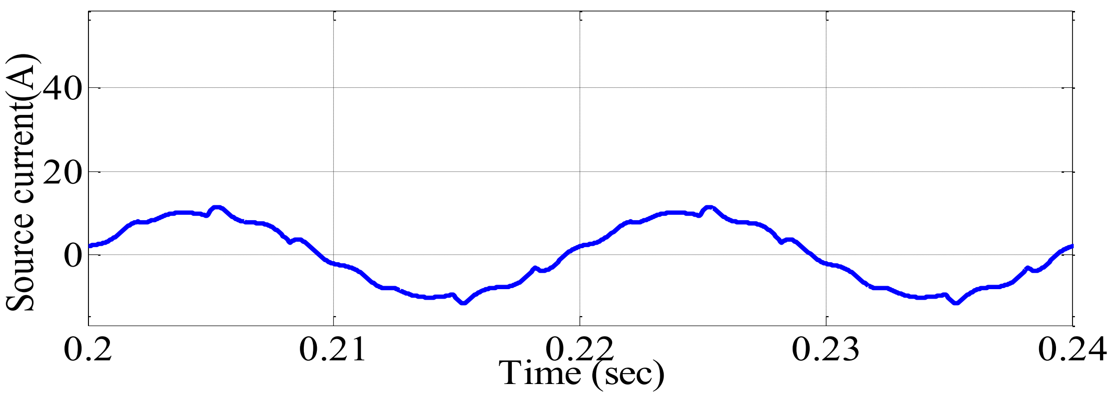


(b)

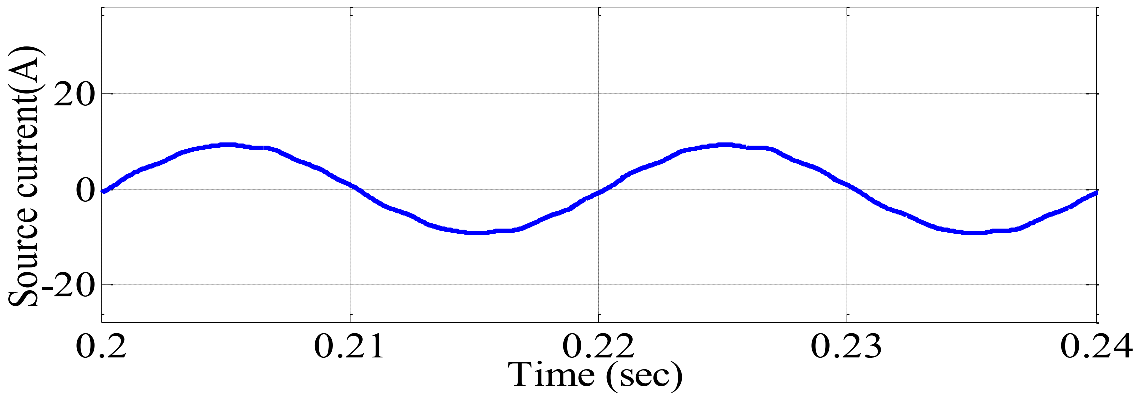


(c)

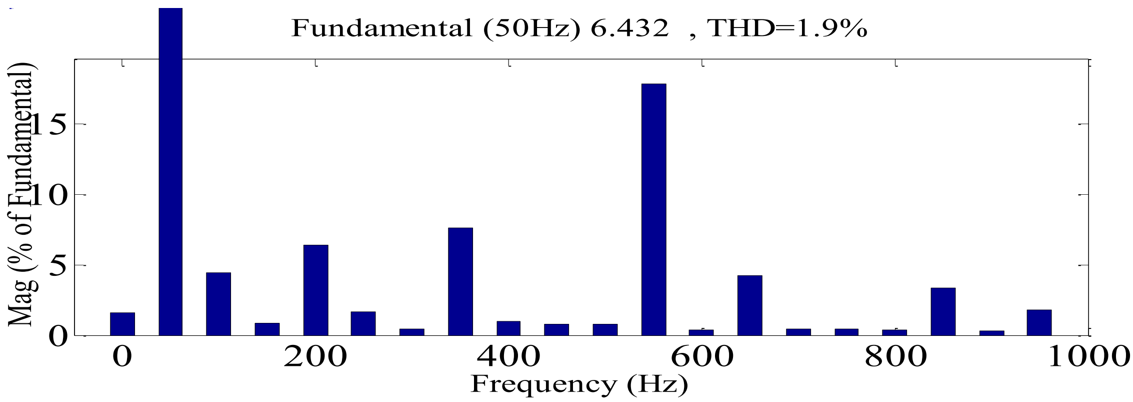
Figure4.5 Simulation Results with RL Load (a) Source current when passive filter is connected (b) Source current when both passive and active filter are connected (c) THD of source current when both filters are connected.



(a)



(b)



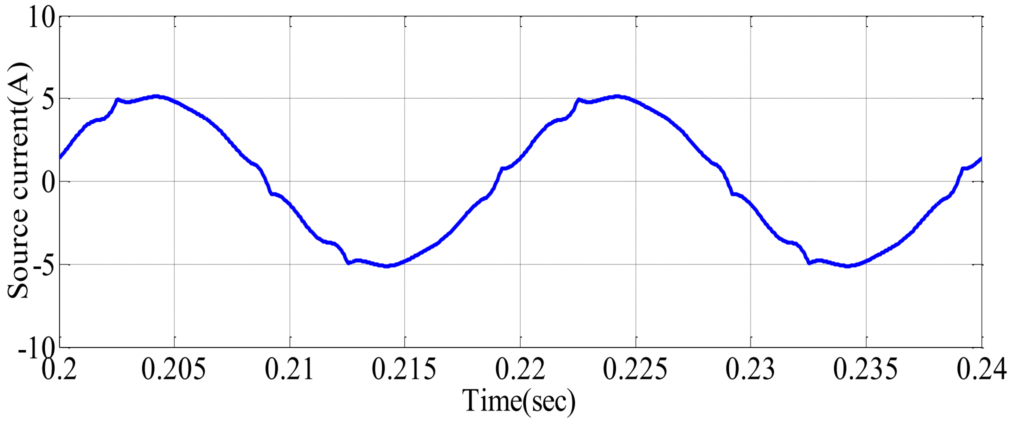
c)

Figure4.6 Simulation Results with RC Load (a) Source current when passive filter is connected (b) Source current when both passive and active filter are connected(c)THD of Source current when both passive and active filter are connected

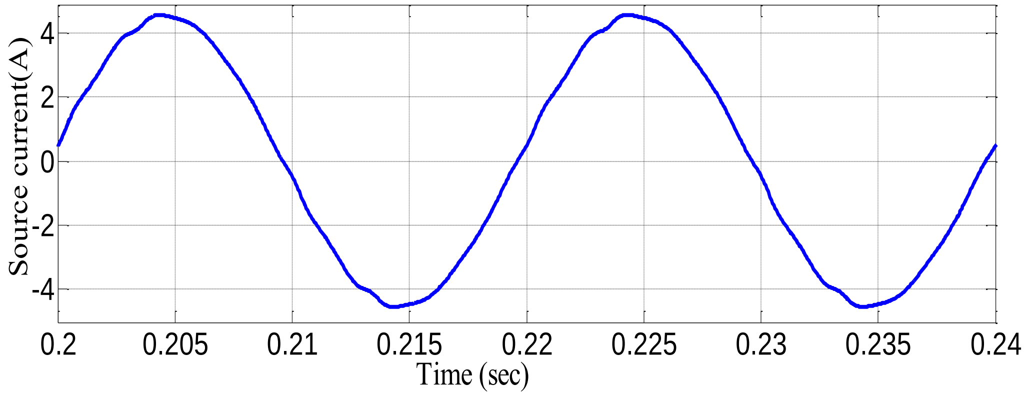
Thus, from the above results it is clear that the harmonic filtering is effected when the source impedance is less than the filter impedance. Hence, to have better performance characteristics the source impedance should be always greater than the passive filter impedance.

4.2.3 When the DC Load Resistance Value is Changed:

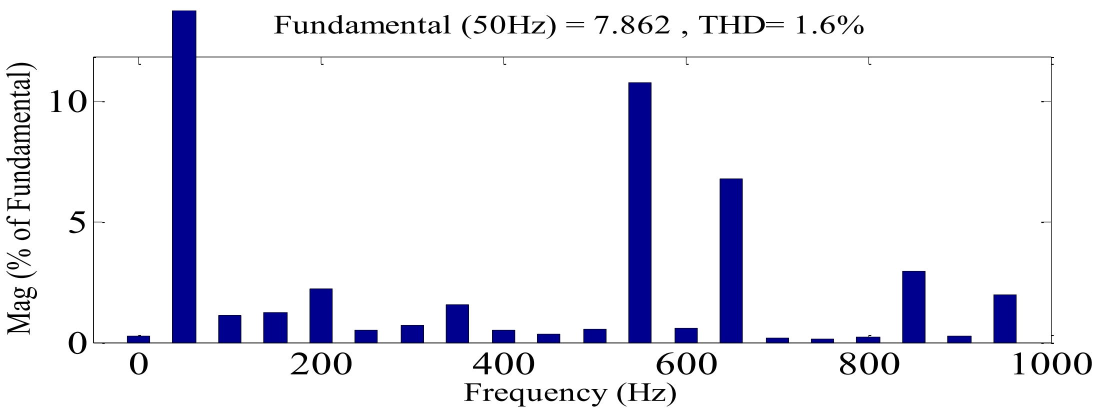
In general, the power system experiences variable load conditions. Therefore, to analyze the system behavior under variable load conditions, this simulation is carried out and the results are shown in Fig. 4.7 and Fig. 4.8 for RL and RC loads respectively. Here the DC resistance value is increased to 50 Ω from its previous value.



(a)

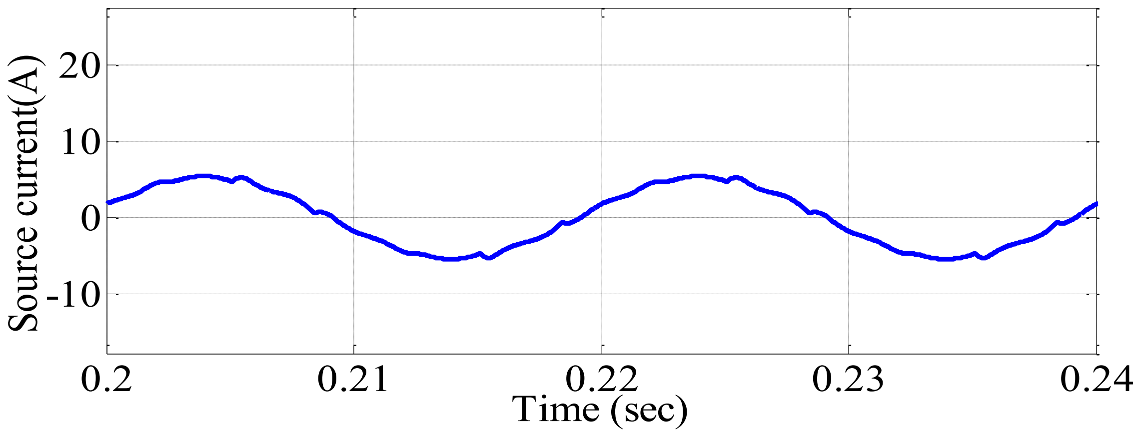


(b)

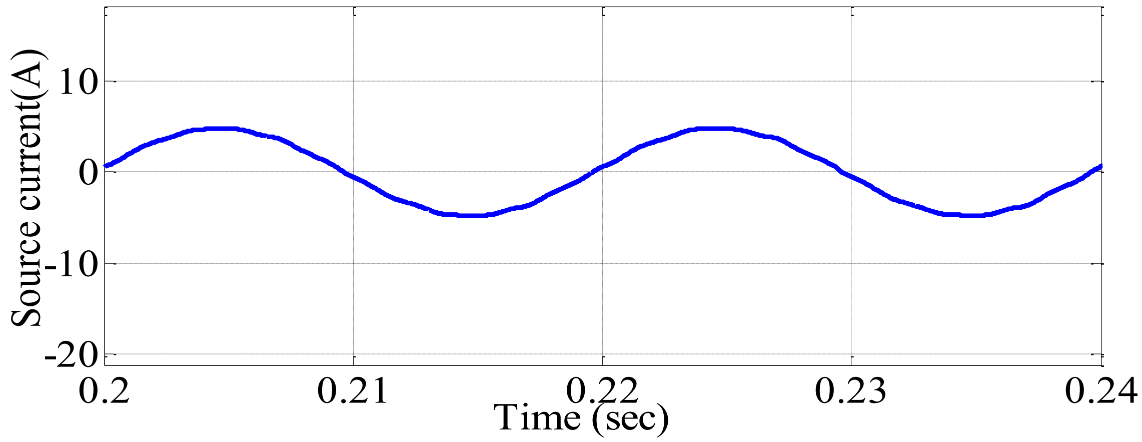


(c)

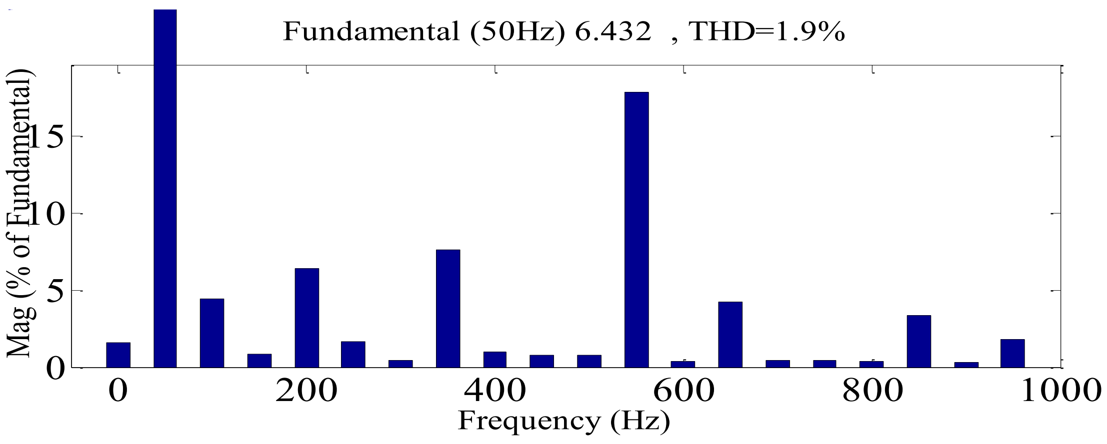
Figure4.7 (a) Source current when passive filter is connected with DC resistance of 50 Ω with RL Load (b) Source. Current when both passive and active filter are connected (c) THD of source current when both filters are connected



(a)



(b)



(c)

Figure4.8 (a) Source current when passive filter is connected with DC resistance of 50 Ω with RC Load (b) Source current when both passive and active filter are connected(c) Source current when both passive and active filter are connected

4.2.4 Comparative Study Under Balanced Load Condition:

A comparative study is made to analyze the performance of the system at various operating conditions when operating with balanced load. The comparison is given in Table- III. From the results it is clear that the system behavior is improved when active filter is connected and the source current THD is very less and is within the IEEE permissible standards.

TABLE-III COPMARISON OF SOURCE CURRENT THD UNDER BALANCED LOAD

NAME	THD with only Passive Filter	THD with Active & Passive Filters
RL load with actual system parameters	5.7%	1.3%
RL load with source impedance L_s = 2.34 mH and R_s = 1.3 Ω	10.6%	1.4%
RL load with the resistor on the dc side is 50 ohm	4.6%	1.6%
RC load with actual system parameters	4.5%	1.62%
RC load with source impedance L_s = 2.34 mH and R_s = 1.3 Ω	8.9%	1.9%
RL load with the resistor on the dc side is 50 ohm	4.4%	1.9%

4.3 SIMULATION RESULTS WITH UNBALANCED LOAD

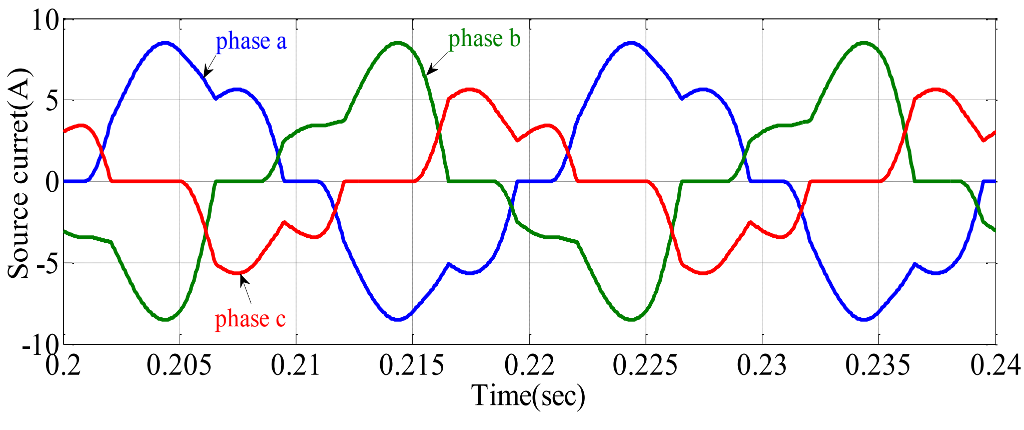
The power system may experience unbalanced load conditions at many times. Thus, the behavior of the proposed control strategy is analyzed by simulating it under unbalanced loading conditions. Here the unbalanced load is created by connecting three single-phase uncontrolled rectifiers with capacitor and resistor in parallel on the DC side. The load values are given Table-IV.

TABLE-IV VALUES IN UNBALANCED CONDITION LOAD

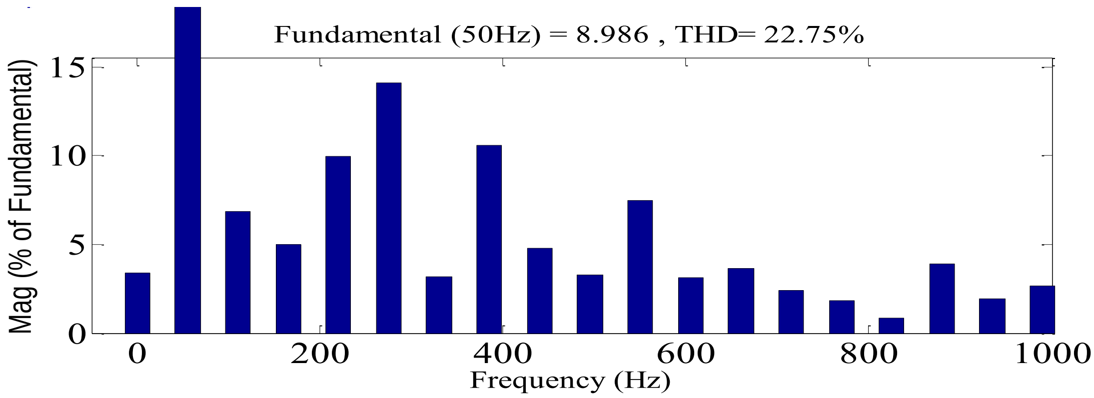
Phase	**C**	**R**
Phase a	2200µF	16.67Ω
Phase b	2200µF	25Ω
Phase c	2200µF	50Ω

4.3.1 With the Actual System Parameters:

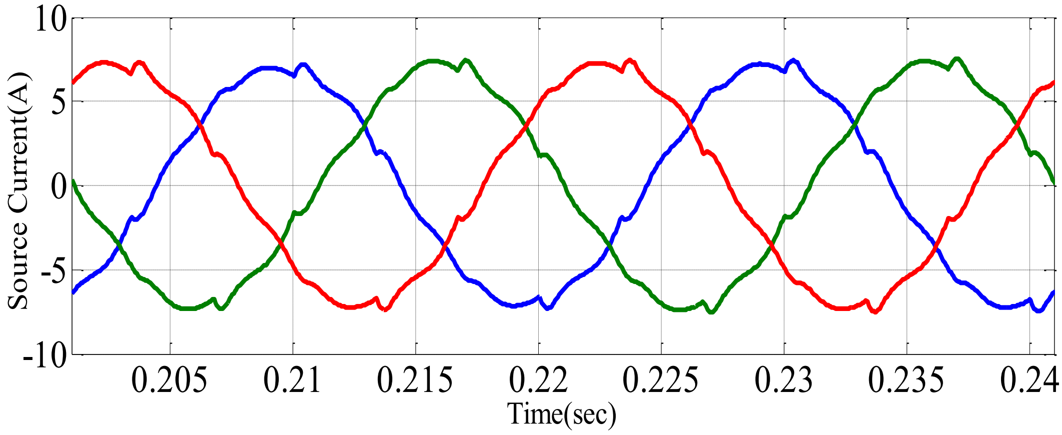
The proposed control strategy is simulated with actual system parameters given in Table-I with unbalanced load values given in Table-IV. The three phase source current waveform is shown in Fig. 4.9. Fig. 4.9 (a) shows the source current waveform without any compensation. From the waveform it is clear that there many harmonics present in the system. Fig.4.9 (c) shows the source current waveform with passive filter. Thus, to reduce these harmonics, APF is connected and then the source current is changed as shown in Fig. 4.9 (e). It is clear from the figure that the three phase source current is almost sinusoidal. Hence, the system performance is improved by connecting the APF even under unbalanced load conditions.



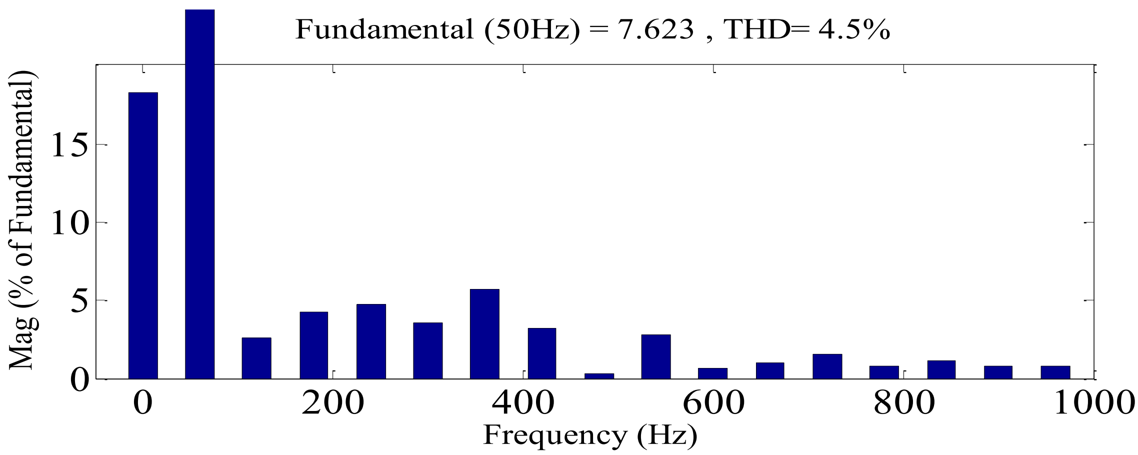
(a)


Fundamental (50Hz) = 8.986 , THD= 22.75%
Mag (% of Fundamental)
15
10
5
0
0
200
400
600
800
1000
Frequency (Hz)

(b)


10
5
0
-5
-10
Source Current(A)
0.205
0.21
0.215
0.22
0.225
0.23
0.235
0.24
Time(sec)

(c)


Fundamental (50Hz) = 7.623 , THD= 4.5%
Mag (% of Fundamental)
15
10
5
0
0
200
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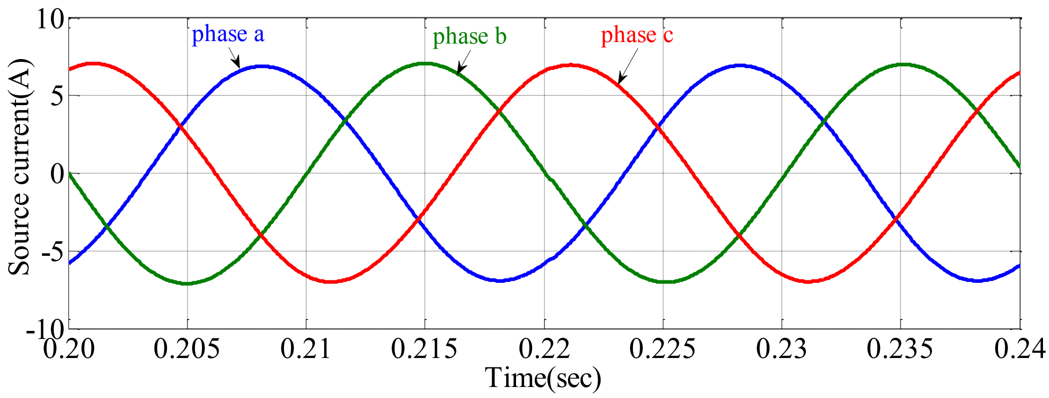
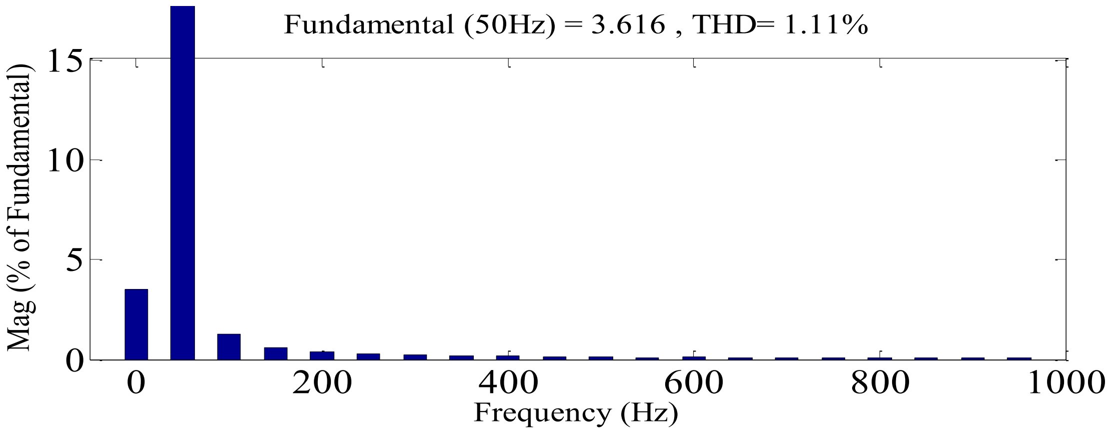
600
800
1000
Frequency (Hz)

(d)



(e)

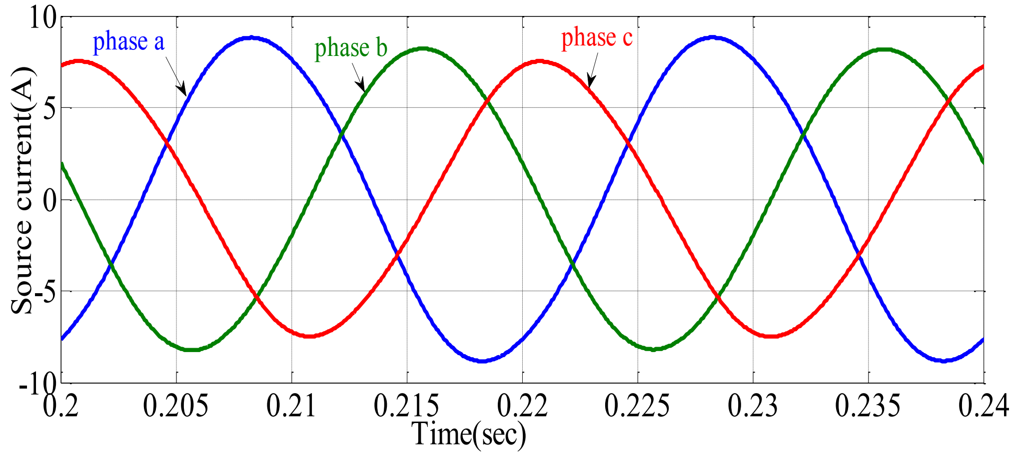


(f)

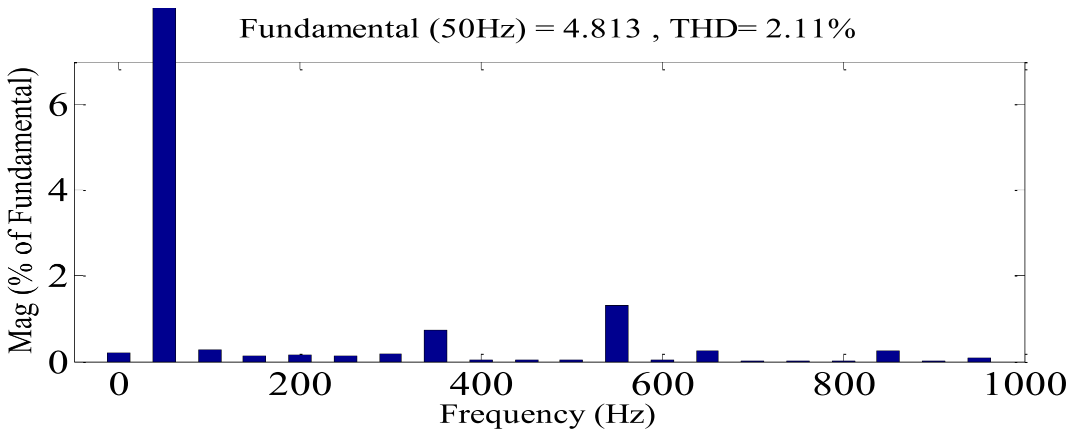
Fig.4.9 Simulation results under unbalanced load (a) Source Current without any Compensation (b) THD of Source Current without any Compensation (c) Source Current with PF (d)THD of Source Current with PF (e) Source Current with both filter (f) THD of Source Current with both filter

4.3.2 When the Source Impedance is Changed:

The source impedance of the system is reduced from its previous value given in Table-I and the new values are- L_s = 2.34 mH and R_s = 1.3 Ω. The simulation results are presented in Fig. 4.10.As in balanced load conditions, even under unbalance condition the system behavior is affected if the source impedance is less than the filter impedance. Thus, the filter design should be done in such a way that the filter impedance is always less than the source impedance.



(a)



(b)

Figure4.10 (a) Source Current with APF under unbalanced load with Source impedance of 1.3 ohm and 2.34 mH(b)THD of Source Current with APF under unbalanced load with Source impedance of 1.3 ohm and 2.34 mH.

4.3.3 Comparative Study Under Unbalanced Load Condition:

A comparative study of the three phase source current THD during unbalanced load at various operating conditions is presented in Table-V. From these results it is clear that the proposed control strategy works better at almost all operating conditions and thus helps in improving the quality of electric power delivered to the end user.

TABLE-V COPMARISON OF SOURCE CURRENT THD UNDER UNBALANCED LOAD

NAME	THD			P.F
	Phase a	Phase b	Phase c	
source current without filter	22.75%	35.0%	37.6%	0.941
source current with passive filter	4.5%	4.3%	5.1%	0.977
source current with both filter	1.4%	1.1%	1.3%	0.99
source current with both filter and source impedance of 1.3 ohm and 2.34 mH	1.8%	1.5%	2.1%	0.99

4.4 CHAPTER SUMMARY:

This chapter presents the MATLAB SIMULINK results of the proposed control strategy at different operating conditions. The system is simulated with both balanced and unbalanced load. And also the behavior of the system with variable loads and with change of source impedance is also studied. From the results it is inferred that the Active Power Filter is very helpful in improving the power quality of the system by filtering out the harmonics.

Chapter5

CONCLUSION AND SCOPE OF FUTUREWORK

Conclusions

Future scope

5.1 CONCLUSIONS

The demand for electric power is increasing at an exponential rate and at the same time the quality of power delivered became the most prominent issue in the power sector. Thus, the reduction of harmonics and improving the power factor of the system is of utmost important. In this project a solution to improve the electric power quality by the use of Active Power Filter is discussed. From the study of Active Power Filter for power quality improvement the following conclusions are drawn-

- Most of the loads connected to the system are non-linear which are the major source of harmonics in the system
- The non-linear load draws non-linear current from the supply
- Thus the voltage at PCC is also non-linear affecting the performance of end user equipment
- To compensate the load harmonics a filter is connected at the PCC which injects the compensating current
- To achieve this a Hybrid power filter with series connected APF and shunt connected passive filter is used
- The APF is controlled based on the Dual Instantaneous Reactive Power Theory to compensate the load harmonics
- Simulation of the proposed control strategy show the behavior of APF under different operating conditions
- The connection of APF improves the passive filter characteristics in addition to improve the system performance
- The APF works well even with variable loads and improves the power factor of the system
- The simulation is also carried out with unbalanced load and found that the APF improves the system behavior by reducing the harmonics

Therefore, it is concluded that the hybrid filter consisting of series APF and a shunt passive filter is a feasible economic solution for improving the power quality in electric power system.

5.2 FUTURE SCOPE:

The work done in this project can be further extended such new improvements can be found. The feasible options are-

- To simulate the proposed control strategy with grid faults and study the behavior of APF in power quality improvement
- To implement the control strategy using Artificial Intelligence (AI) techniques

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